and $3A$ involve parity change while $4T$ and $4V$ do not, the $K^{40} \rightarrow Ca^{40}$ transition can only be $3T$ or $3A$ (or both). The parity change, the lifetime, and the spin change of four eliminate Fermi interactions from this particular transition. $3T$ and $3A$ are third forbidden Gamow-Teller interactions.

The shape of the beta spectrum of K^{40} is consistent with the theoretical shape uniquely predicted by beta theory using the known spin change and the parity change given by the shell model. The measured K^{40} spectrum, however, does not seem to eliminate any of the five types of interaction for beta decay in general.

I would like to thank Professor Robley D. Evans for his advice and encouragement throughout this work.

PHYSICAL REVIEW VOLUME 91, NUMBER 4 AUGUST 15, 1953

Experimental Evidence for the Fermi Interaction in the β Decay of O^{14} and C^{10}†

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(Received April 17, 1953)

The γ-ray spectra of O^{14} and C^{10} have been investigated with a NaI scintillation spectrometer. A value of 2.30 ± 0.03 Mev was found for the O^{14} nuclear γ ray. C^{10} has two γ rays with energies 723 ± 15 and 1033 ± 30 kev; the number of quanta per disintegration are 0.99 ± 0.08 and $1.65\pm0.20\times10^{-2}$, respectively. The 1033-kev γ ray is associated with a weak positron transition to the 1.74-Mev level in B^{10}. There are less than 10^{-3} transitions per disintegration to the 2.15-Mev level of B^{10}. By combining our results with those of heavy particle reactions and using the predictions of the charge multiplet theory on the energies of the analog states, we conclude that the O^{14} decay and the weak C^{10} branch to the 1.74-Mev level of B^{10} are allowed favored $0\rightarrow0$ (no) transitions. From the C^{10} data we find that the ratio of the Fermi to the Gamow-Teller interactions constants $(G_F{}^2/G_{GT}{}^2)$ is $0.79_{-0.13}^{+0.27}$, if one assumes $L-S$ coupling, and $0.44_{-0.07}^{+0.15}$ for $j-j$ coupling.

I. INTRODUCTION

IN 1948 some of the main features of the decays of O^{14} and C^{10} were reported.[1] O^{14} was found to disintegrate to an excited state of N^{14} at 2.3 Mev through an allowed positron transition (see Fig. 1). The energy of this excited state corresponded closely to the value calculated for the state in N^{14} which is the $N=Z$ component of the $T=1$ charge multiplet to which the ground states of C^{14} and O^{14} belong. The N^{14*} level at 2.3 Mev appearing in the O^{14} decay was therefore assumed to be this state. (We shall hereafter refer to the charge multiplet state as the analog state.) Since the ground state of C^{14} is known to have spin 0, this identification leads to the interpretation of the $O^{14}-N^{14*}$ decay as a $0\rightarrow0$ (no) β transition which requires the Fermi interaction in the theory of β decay. Subsequent to these experiments, the evidence accumulated on the properties of other β transitions seemed to point, with few exceptions, to a satisfactory description of the β decay process in terms of the Gamow-Teller interaction.[2] Re-examination of O^{14} and C^{10} was undertaken to throw more light on this question.

† A preliminary report of this work was presented at the New York meeting of the American Physical Society January 1952 [Phys. Rev. **86**, 619 (1952)]. This work has been supported in part by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

[1] Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).

[2] A. Feingold and E. P. Wigner (unpublished communication); C. Wu, Revs. Modern Phys. **22**, 386 (1950).

II. GAMMA RADIATION OF O^{14}

First consideration was given to a better determination of the energy of the 2.3-Mev γ ray in the O^{14} decay, for comparison with the same energy γ ray found in N^{14} in other reactions.[3,4] A NaI(Tl) scintillation spectrometer was used to compare the photopeak of the 1.28-Mev Na^{22} γ ray with the pair peak of the O^{14} γ ray.[5] This measurement gave an energy of 2.30 ±0.03 Mev for the latter γ ray. Thomas and Lauritsen found a 2.310 ± 0.012-Mev γ ray in the $C^{13}(d,n)N^{14}$ reaction.[6] The calculation of the energy of the analog state in N^{14}, using recent empirical data, leads to a value of 2.31 Mev.[7] The close agreement of these numbers constitutes strong support for the identification of the 2.3-Mev level as the analog state in N^{14}.

Recent experimental observations of the reactions $O^{16}(d,\alpha)N^{14}$ [8] and $N^{14}(d,d')N^{14}$ [9] have been especially interesting because of the absence of α particles and

[3] W. F. Hornyak *et al.*, Revs. Modern Phys. **22**, 291 (1950).

[4] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[5] W. W. Bell, Senior thesis, Princeton University, 1951 (unpublished).

[6] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).

[7] E. Feenberg and G. Goertzel, Phys. Rev. **70**, 597 (1946); E. Feenberg, Nuclear Physics Lecture Notes (unpublished).

[8] Burrows, Powell, and Rotblat, Proc. Roy. Soc. (London) **209**, 478 (1951); A. Ashmore and J. F. Raffle, Proc. Phys. Soc. (London) **A64**, 754 (1951); Van de Graaf, Sperduto, Buechner, and Enge, Phys. Rev. **86**, 966 (1952).

[9] Bockelman, Browne, Sperduto, and Buechner, Phys. Rev. **90**, 340 (1953); Browne, Bockelman, Buechner, and Sperduto, Phys. Rev. **90**, 340 (1953).

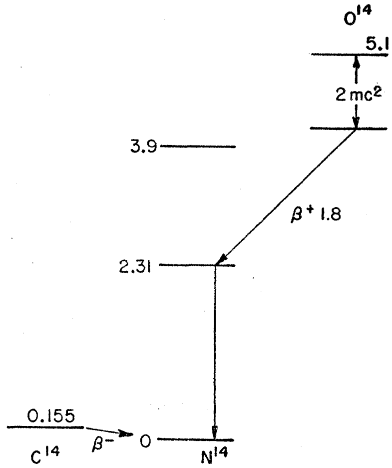

FIG. 1. Decay scheme for O^{14}.

inelastically scattered deuterons corresponding to the excitation of the 2.3-Mev level. Adair[10] has shown that if the isotopic spin is a good quantum number, these reactions cannot lead to a charge state with $T=1$. He concludes that the failure to excite the N^{14*} level at 2.3 Mev is consistent with the assumption that it is the analog state in N^{14}. Adair's discussion is based on the assumption that charge-dependent interactions (the neutron-proton mass difference and the Coulomb interaction between protons) do not invalidate selection rules derived from the theory of a charge independent Hamiltonian. Radicati[11] investigated the importance of Coulomb forces in mixing states with different isotopic spin and concluded that the mixing is too small to affect the isotopic spin selection rules. Similar conclusions about the N^{14*} state have been reached by Kroll and Foldy[12] through the use of selection rules based on charge symmetry.

The available experimental evidence, supported by reasonable theoretical considerations, indicates that the N^{14*} level to which the O^{14} decays has spin 0 and even parity. It seems highly probable that the allowed (favored) O^{14} positron decay requires the existence of a strong Fermi interaction.

III. GAMMA-RADIATION OF C^{10}

At the time of our earlier investigation of C^{10}, the low-lying energy levels of B^{10} were thought to be at 0.72 and 2.17 Mev. The latter level was assumed to be the analog of the Be^{10} and C^{10} ground states. However, Ajzenberg[13] has shown the existence of an additional level at 1.74 Mev; this result has been amply confirmed by others[4] (see Fig. 2).

The calculation of the excitation energy of the analog state in B^{10} requires knowledge of Coulomb exchange integrals;[7] with the available semi-empirical estimates, these calculations give about 1.9 Mev. Therefore, either the 1.74- or the 2.15-Mev level could be the analog state.

We have attempted to find evidence for β^+ transitions from C^{10} to the 1.74- and 2.15-Mev states of B^{10}. The main transition goes to the level at 0.72 Mev. Estimates of the transition probabilities for β decay to the higher levels are given in Table II. It appeared most promising to examine the γ spectrum for the presence of 1.03-, 1.43- and 2.15-Mev radiation coming from the 1.74- and 2.15-Mev levels (Fig. 2).

C^{10} was obtained by bombarding B^{10} powder with 18-Mev protons, using an internal probe.[1] Radioactive gases were swept out of the probe with helium through a trap filled with ascarite which absorbed C^{10} in the form of CO_2. By using continuous flow, a moderately constant source strength was maintained.

A typical pulse spectrum for the γ rays of C^{10} obtained with a NaI(Tl) scintillation spectrometer[14] is shown in Fig. 3. The data were recorded with a 10-channel discriminator which could be set to examine

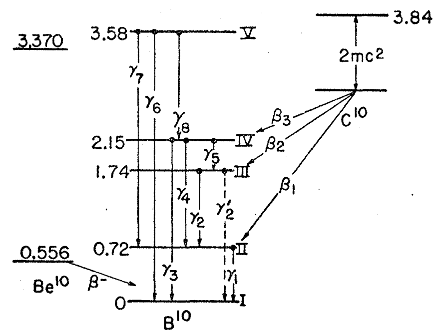

FIG. 2. Decay scheme for C^{10}.

different portions of the spectrum with 2- or 5-volt channels. The source strength was monitored with a single channel discriminator set on the 51-volt peak. The prominent peaks at 36.5 and 51 volts are the photopeaks of 0.511- and 0.72-Mev quanta. Beyond these one sees a weak peak at 74 volts superimposed on a continuous distribution of pulses. This continuum has been observed out to pulse amplitudes corresponding to 2 Mev and was shown to be caused by γ rays arising from the annihilation of the positrons of C^{10} in flight by comparison with the Ne^{19} γ-ray pulse spectrum. Ne^{19} has essentially the same positron spectrum as C^{10} and has no nuclear γ radiation. The Ne^{19} spectrum is shown in Fig. 3 normalized to the C^{10} 511-kev photopeak, after the latter was corrected for C^{11} (arising from B^{11} in the target) and for the Compton distribution of the 0.72-Mev γ ray.

A number of tests were made to establish the character of the peak at 74 volts. The possibility that it arose from pile-up or from coincidences (of 511- and

[10] R. F. Adair, Phys. Rev. **87**, 1041 (1952).
[11] L. A. Radicati, Proc. Phys. Soc. (London) **A66**, 139 (1953).
[12] N. M. Kroll and L. L. Foldy, Phys. Rev. **88**, 1177 (1952).
[13] F. Ajzenberg, Phys. Rev. **82**, 43 (1951).
[14] R. Hofstadter and J. A. McIntyre, Phys. Rev. **78**, 617 (1950); **80**, 631 (1950).

723-kev radiation) was eliminated by varying the counting rate and source position. Because of low intensity, attempts to determine the half-life of the 74-volt peak did not give accurate results. However, the results are consistent with the 19.1-sec half-life of C^{10}. The spectrum in Fig. 3 was obtained consistently under a wide variety of conditions of proton-bombarding energy and current. For chemical identification, the radioactive gases generated in the cyclotron probe were swept through a tube of ascarite, a tube containing CuO, and finally through the ascarite trap at the scintillation spectrometer. When the first (ascarite) tube was by-passed, we obtained the usual activity of C^{10}. When the gases passed through the first tube, the activity dropped by a factor of 12. The CuO was then heated to about 500°C to convert CO from the probe, if it were present, to CO_2 which would again be trapped

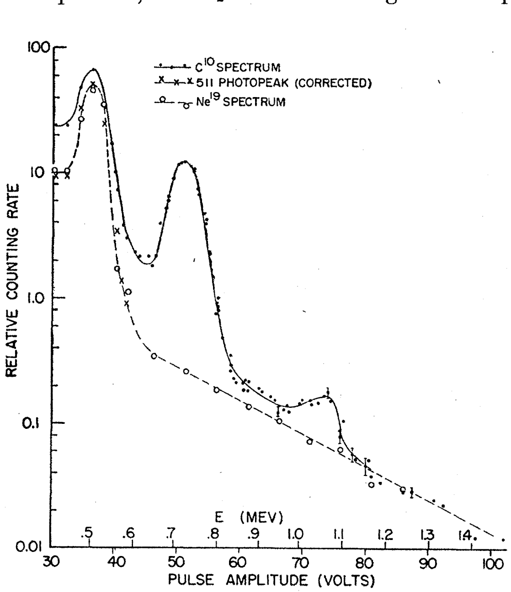

FIG. 3. Scintillation spectrum of γ radiation of C^{10}.

by the ascarite at the source position. We found that the activity increased to half its original value, and the same pulse-height spectrum was obtained as before. On the basis of the above tests, we feel confident that the 74-volt peak is due to a γ ray of C^{10}.

Calibration of the energy scale of the spectrometer with the well-known γ rays of Cs^{137}, Zn^{65}, and Na^{22} lead to 723±15 kev and 1033±30 kev for the energies of the nuclear γ rays of C^{10}. These are in good agreement with the values obtained by Rasmussen, Hornyak, and Lauritsen[15] in the γ-spectrum of the $Be^9(d, n)B^{10}$ reaction; 716.6±1 and 1022±2 kev, respectively. The second of the γ rays arises from transitions between the 1.74-Mev and 0.72-Mev levels in B^{10}, the first one from the transition from the 0.72-Mev level to the ground state (see Fig. 2). No softer γ rays were ob-

[15] Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949).

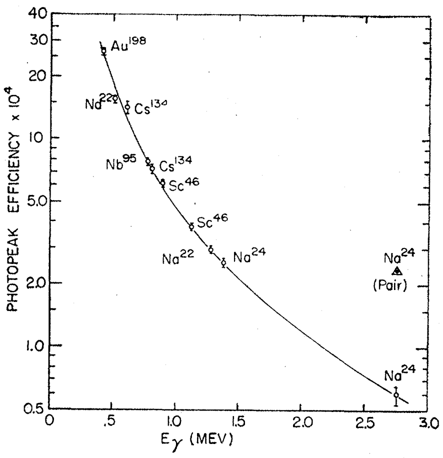

FIG. 4. Photopeak efficiency curve for NaI(Tl) crystal (1-cm cube). The ordinates give the absolute efficiency, if the source is 1.9 cm from the center of the crystal.

served. A specific search was made for 1.4- and 2.1-Mev radiation, with negative results which will be discussed later.

The existence of the 1033-kev γ ray indicates that there is a weak positron branch to the 2.15- or 1.74-Mev level in B^{10}. In order to interpret the present data, it was necessary to obtain a photopeak efficiency curve for the NaI(Tl) spectrometer. Using the well-known $\beta-\gamma$ coincidence methods, the curve in Fig. 4 was obtained for our NaI(Tl) crystal (1.0-cm cube). The sources were about 2 mm in diameter and were placed 1.9 cm from the center of the crystal. There were approximately 2 mm of aluminum and 1 mm of Pyrex between the source and crystal. The β particles were detected with a thin anthracene scintillator. The coincidence spectrum was recorded with the 10-channel discriminator, thereby enabling us to determine the absolute photopeak efficiency for each γ ray (for the geometry specified above).

The sources used for each point are identified in Fig. 4. The efficiency at 511 kev was obtained from the ratio of the 511-kev and the 1.28-Mev photopeaks of Na^{22}, and the measured efficiency for the latter. (It was assumed that there is no K capture in Na^{22}.) The 600-kev point (Cs^{134}) may be in doubt, since recent work[16] indicates considerable complexity in the decay scheme of the isotope. The measured efficiencies are 20 to 40 percent higher than the values calculated from tabulated photoelectric cross sections and the geometry used in the energy range 0.4 to 1.4 Mev. This increase in efficiency is to be attributed to photoabsorption following single or multiple Compton scatterings within the crystal, as pointed out by Hofstadter and McIntyre.[14] Tests with sources at various distances from the crystal showed that the relative efficiency as a

[16] F. H. Schmidt and G. L. Kaister, Phys. Rev. **86**, 632 (1952); J. M. LeBlanc *et al.*, Phys. Rev. **89** 907 (1953).

TABLE I. Gamma rays of $Be^9(d, n)B^{10}$.

γ-ray	$E\gamma$	Relative yield $Y(\gamma)^a$
γ_5	413.5±1	1.2
γ_1	716.6±1	13.7
γ_2	1022 ±2	3.9
γ_2'	(1740)	(<0.4)[17]
γ_4, γ_8	1433 ±5	2.5
γ_3	2151 ±16	1.2
γ_7	2871 ±15	2.4
γ_6	3604 ±30	0.9

[a] Probable error = 25 percent.

function of energy was independent of source to crystal distance within 3 percent up to 7 cm.

Analysis of the C^{10} pulse-height spectrum yielded 3.46±0.17 for the ratio of the area of the annihilation photopeak to the area of 723-kev photopeak. (This ratio has been corrected for the relative absorption of the γ rays in the brass used to prevent the positrons from reaching the crystal.) If every positron annihilated at rest, there would be two 511-kev quanta per positron. However, about 5 percent of the positrons annihilate in flight. Taking this into account and using the efficiencies given in Fig. 4, we find that the number of 723-kev quanta per positron is 0.99±0.08.

Similar analysis gave 120±10 for the relative areas of the 723-kev photopeak and the 1033-kev photopeak. Combining this with the efficiencies for these two energies, we find that there are $(1.65\pm0.20)\times10^{-2}$ 1033-kev quanta per 723-kev quantum.

Since positron decay to the 2.15-Mev level in B^{10} would give rise to 2.15-, 0.414-, and possibly 1.433-Mev radiation,[15,4] upper limits for their intensity were set. Because its spectrum would be obscured by the presence of the harder radiations, we could not make a sensitive estimate for the 0.414-Mev γ ray. From the counting rates at the positions of the photopeaks, we estimate that

$$n(1.43)/n(1.03)<\tfrac{1}{8} \quad\text{and}\quad n(2.15)/n(1.03)<1/70,$$

where $n(E)$ is the number of quanta of energy E per disintegration.

These results may be compared with the measurements of Rasmussen *et al*,[15,17] on the relative intensities of the γ rays observed in the $Be^9(d, n)B^{10}$ reaction. These are partially reproduced in Table I. (See Fig. 2.)

Since the Q of this reaction is high, the yield of any particular γ ray is the sum of neutron emission to a state and γ-ray cascades to this state from higher states. However, the relative yields of γ rays from a particular state should be unique. If the 1030-kev γ ray which we find in the decay of C^{10} follows a positron transition to the 2.15-Mev level in B^{10}, we would expect

$$n(1.43)/n(1.03)=Y(\gamma_4)/Y(\gamma_5)=2.5/1.2=2.1$$
(assuming γ_8 does not occur);

$$n(2.15)/n(1.03)=Y(\gamma_3)/Y(\gamma_5)=1.2/1.2=1.0.$$

[17] D. E. Alburger, Phys. Rev. 83, 184 (1951).

These values are clearly inconsistent with the upper limits which we have set (1/8 and 1/70, respectively) from the C^{10} γ-ray spectrum. We conclude that the 1033-kev γ ray in C^{10} is primarily associated with a positron transition to the 1.74-Mev level in B^{10}. From these limits and the data in Table I, we estimate that there is less than one β_3 transition per seventeen β_2 transitions. Therefore, positron transitions to the 2.15-Mev level occur in less than 0.1 percent of the C^{10} disintegrations. (If some of the 1.43-Mev quanta observed in the Be+d reaction are ascribed to transitions from the 3.58-Mev level to the 2.15-Mev level, this limit will be slightly reduced.) Our conclusions are summarized in Table II. Column 1 lists the positron transitions (see Fig. 2). Column 2 gives the maximum β^+ energies. The earlier result[1] on the maximum energy of the β_1 spectrum, 2.2±0.1 Mev, was based on an analysis of an absorption curve; under similar conditions the maximum energy of Ne^{19} positrons was found to be 2.3±0.1 Mev. Recent spectrometer measurements[18] on Ne^{19} give 2.18±0.03 Mev for the latter, while measurement of the threshold for the $F^{19}(p, n)Ne^{19}$ reaction[19] leads to an expected end point of 2.235±0.005 Mev. These results indicate that the absorption analyses gave energies about 100 kev high. Consequently, we have taken the C^{10} β_1 spectrum to have an energy of 2.10 Mev, with an uncertainty of the order of 100 kev.

TABLE II. Relative positron transition probabilities.

$C^{10}-B^{10}$ transition	Maximum energy of transition	Energy of B^{10} level	Relative transition probabilities Exp (percent)	Theor ($f\times1.25$)
β_1	$2.1_0\pm0.1$	0.72	98.4	100_{-12}^{+25}
β_2	$1.0_8\pm0.1$	1.74	1.65±0.20	$6.4_{-2.3}^{+2.6}$
β_3	$0.6_7\pm0.1$	2.15	<0.1	$0.94_{-0.44}^{+0.62}$

Column 3 in Table II gives the energy of the final state in B^{10}, while column 4 summarizes our present results. Column 5 gives the relative transition probabilities, assuming that the matrix elements and interaction constants are identical and that the transitions are allowed. These transition probabilities are proportional to the f values which depend on the energy of the positron transitions and on the nuclear charge. Using graphs for the f values,[20] we obtain the relative values listed in column 5; the + and − values correspond to the changes introduced by ±100 kev in the energies of the transitions. (The f values may be obtained by dividing by 1.25.) The approximate agreement between columns 4 and 5 for β_1 and β_2 shows that both transitions are allowed.

[18] G. Schrank and J. R. Richardson, Phys. Rev. 86, 248 (1952).
[19] H. B. Willard *et al.*, Phys. Rev. 85, 849 (1952).
[20] E. Feenberg and G. Trigg, Revs. Modern Phys. 22, 399 (1950); A. Feingold (privately circulated).

IV. DISCUSSIONS OF LEVELS OF B^{10}

We have established the presence of allowed (favored) positron transitions to the 0.72- and the 1.74-Mev levels in B^{10} by combining our results on the γ-ray spectrum of C^{10} with the γ-ray intensities found in the $Be^9(d, n)B^{10}$ reaction of Rasmussen *et al.*[15] We wish now to correlate this information with the considerable knowledge of the B^{10} levels which is summarized in references 3 and 4.

Ajzenberg[21] has shown, by examination of the angular distribution of neutrons arising from the $Be^9(d, n)B^{10}$ reaction, that the parities of all of the levels of B^{10} shown in Fig. 2 are identical and presumably even. Since C^{10} makes allowed transitions to at least two of these levels (II and III), these parity assignments are consistent with the usual assumption that even-even nuclei have even parity in the ground state. If we make the additional usual assumption that the spin of C^{10} is zero, we conclude that levels II and III have spins 0 or 1 in order to be consistent with the selection rules for allowed transitions. The presence of the 1022-kev γ ray eliminates the possibility that both have spin 0.

To go beyond this point, we now consider the γ-ray transition probabilities for comparison with Table I. Accurate formulas for such computations are not available. Goldhaber and Sunyar[22] have found that, for magnetic transitions, Weisskopf's formulas[23] give values in reasonable agreement with experiment, especially so for $M3$ and $M4$ transitions. Electric transitions, on the other hand, show a large variability when compared with theory. Of special interest here are their results on electric quadrupole transitions, which, in the main, are slower (by as much as a factor of 1000), although occasionally faster (by a factor of 50). They also note occurrence of $M1$ and $E2$ mixed transitions in two cases, indicating a slowing down of $M1$ and/or speeding up of $E2$.

Since the levels of B^{10} under consideration have even parity,[21] we need consider only $M1$, $E2$, and $M3$ transitions. Weisskopf's formulas give the following transition probabilities for B^{10}:

$$T(M1)=3.2\times10^{13}E^3 \text{ sec}^{-1},$$
$$T(E2)=3.8\times10^{9}E^5 \text{ sec}^{-1},$$
$$T(M3)=5.6\times10^{2}E^7 \text{ sec}^{-1},$$

with E measured in Mev.

If the spin of level II were zero, γ_1 would be an $M3$ transition (since the ground state spin has been found experimentally to be 3[24]) with a calculated life time of 1.8×10^{-2} sec. From observation of prompt coincidences between β_1 and γ_1, we have found that the lifetime is less than 2×10^{-7} sec. We can conclude that the spin of level II is not 0 and is therefore 1.

TABLE III. Calculated transition probabilities (sec^{-1}).

γ-ray	Transition	Energy (Mev)	$M1$	$E2$	$M3$
γ_2	III–II	1.02	3.4(13)[a]	4.2(9)	—
γ_2'	III–I	1.74	—	6.0(10)	2.7(4)
γ_3	IV–I	2.15	3.2(14)	1.7(11)	1.2(5)
γ_4	IV–II	1.43	9.3(13)	2.2(10)	6.7(3)
γ_5	IV–III	0.413	2.2(12)	4.7(7)	1.1(0)

[a] $a(n)\equiv a\times10^n$.

Calculated transition probabilities for the other γ-ray transitions in B^{10} are listed in Table III. Examination of various sets of spins (IV, III, II, I) shows that (2, 1, 1, 3) gives a spread of transition probabilities of a factor of 145 for γ_3, γ_4, and γ_5, while the experimental value is 2. The sets (1, 1, 1, 3) and (1, 0, 1, 3) give a spread of 550. On the other hand, other combinations (for example, 0, 1, 1, 3 or 3, 1, 1, 3) give variations of the order of 10^7 or greater. It therefore seems reasonable to accept the first three sets as possible ones. (While a spread of 100 to 500 also seems large, the individual matrix elements have to depart from the theoretical values only by the order of the square root of the spread.) Thus, the spin of the 2.15-Mev level (J_{IV}) is 1 or 2, and the spin of the 1.74-Mev level J_{III} is 0 or 1, with the restriction that J_{IV} cannot be 2 if $J_{III}=0$. Consideration of γ-ray transitions from the 3.58-Mev level and of the absence of the cross-over γ ray (γ_2') does not yield additional information about J_{III} and J_{IV}.

In order to limit our choice further, we recall the expectation that there is a spin 0 analog level in B^{10} in the neighborhood of 1.9 Mev. Since the spin of the 2.15-Mev level (J_{IV}) must be 1 or 2, according to the arguments presented above, we conclude that the spin of the 1.74-Mev level (J_{III}) is zero. The latter furthermore restricts J_{IV} to be 1.

In summary, we find that reasonable spin assignments for the first three excited states in B^{10} are $J_{IV}=1$, $J_{III}=0$, and $J_{II}=1$. The assumptions entering this analysis have been that

(1) the C^{10} 1.03-Mev γ ray arises from a transition between the 1.74- and 0.72-Mev levels in B^{10} (rather than from a hitherto unreported level in B^{10} at 1.03 Mev),

(2) the calculations of γ-ray transition probabilities with the Weisskopf formulas are significant to within one or two orders magnitude, and

(3) the theory of charge multiplets applies in detail to the $Be^{10}-B^{10}-C^{10}$ triad.

Our conclusions agree with those of H. T. Richards (unpublished).[4]

Additional confirmation that the spin of the 1.74-Mev level is zero has been adduced by Ajzenberg and

[21] F. Ajzenberg, Phys. Rev. **88**, 298 (1952).
[22] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
[23] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951); V. F. Weisskopf and J. M. Blatt, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 627.
[24] Gordy, Ring, and Burg, Phys. Rev. **74**, 1191 (1948).

Lauritsen[4] on the basis of the conservation of isotopic spin[10,11] in the reaction $B^{10}(d, d')B^{10*}$. Buechner[4,9] and his co-workers have found that, while all of the lower levels in B^{10} are excited by inelastically scattered protons, only the 1.74-Mev level is not excited by deuterons. (See discussion of the 2.31-Mev level in N^{14} earlier in this paper.) Finally, we note that with the above spin assignments the positron transition (β_3) to the 2.15-Mev level should be allowed. Our failure to observe this transition indicates that its nuclear matrix element is much smaller than for allowed favored transitions.

V. IMPLICATIONS FOR THE THEORY OF β DECAY

The present work indicates that β_1 (Fig. 2) is a $0\rightarrow1$ transition and that β_2 is a $0\rightarrow0$ transition. The former is allowed only by the Gamow-Teller interaction and the latter only by the Fermi interaction. A comparison of the relative intensities of the two transitions may be used to compare the strengths of the two interactions. From the Fermi theory of β decay one expects that $G^2|M|^2\,ft$ is a constant for all β transitions, where G^2 is the interaction constant and $|M|^2$ is the nuclear matrix element for the transition. Using this expression for the present transitions β_1 and β_2, we obtain, for the ratio of the Fermi to the Gamow-Teller interaction constants,

$$R=G_F^2/G_{GT}^2=f_1n(\beta_2)\left|\int\boldsymbol{\sigma}\right|^2\Big/f_2n(\beta_1)\left|\int1\right|^2,$$

where we have used the fact that the ratio of lifetimes for the two transitions is inversely proportional to the ratio of the relative number of positrons $n(\beta)$ per disintegration. $|\int1|^2$ and $|\int\boldsymbol{\sigma}|^2$ are the appropriate nuclear matrix elements for the two interactions. For $L-S$ coupling one obtains the values 2 and 6, respectively.[25,26] Combining the latter with the data of Table II, we obtain

$$R_{L-S}=0.79_{-0.13}^{+0.27}.$$

With the $j-j$ wave functions, the Fermi matrix element is unchanged (it is independent of coupling schemes as long as one assumes charge independence), but the Gamow-Teller matrix element is reduced to 10/3. Consequently,

$$R_{j-j}=0.44_{-0.07}^{+0.15}.$$

Analyses of allowed transitions by Trigg,[26] Kofoed-Hansen[27] and Nataf and Bouchez,[28] indicate a decided preference for $L-S$ wave functions for the light nuclei. Their conclusions indicate that R is in the region 0.8 to 1.0. Moszkowski[29] had concluded earlier that it is much smaller, by comparing ft values of the neutron decay and He^6. However, the discovery by Dewan *et al.*[30] and the subsequent confirmation by Wu *et al.*,[31] that the earlier He^6-Li^6 mass difference was in error invalidates Moszkowski's conclusion. Recalculation[31] indicates a value of $R\leq1.4$. Konopinski and Langer[32] obtained a value of 1.4 ± 0.7 from a comparison of H^3 and He^6 and $0.8_{-0.3}^{+0.5}$ from O^{14} and He^6. Blatt[33] suggests that the value of the matrix element for the He^6 decay is too uncertain to use in this connection and prefers to compare the O^{14} and H^3 decay, from which he obtains $0.54_{-0.25}^{+0.5}$. Feenberg (private communication) has made a comprehensive and detailed analysis of the light nuclei and their magnetic moments similar to those of references 26, 27, and 28 and concludes that G_F^2/G_{GT}^2 probably lies between 0.75 and 1.15. It is evident from this summary that an accurate determination of R requires higher experimental precision and a better knowledge of nuclear wave functions than are at present available.

Perhaps a critical test of the expected constancy of $G^2|M^2|\,ft$ may be found in the comparison of the ft values of the $0\rightarrow0$ transitions in the C^{10} and O^{14} decays. If nuclear forces are charge-independent, the value of $|M^2|$ is independent of the coupling schemes for these transitions. Thus we expect the ft values of $C^{10}(0\rightarrow0)$ and O^{14} to be identical. From the present data and our previous results[1] we find, for O^{14}, $(ft)=3300\pm750$ and, for the $C^{10}(0\rightarrow0)$, $ft=5900\pm2400$. The large uncertainties in these values arise primarily from the uncertainties in determining the positron energies by absorption measurements. While these ft values agree within the rather large limits of error, it is hoped that accurate measurements of the positron energies will make it possible to arrive at more definite conclusions regarding this question and those discussed above.

We are very much indebted to Professor E. Feenberg for his stimulating and critical discussion of this work and for permitting us to quote his unpublished results; and to Dr. B. C. Carlson for his generous assistance in making various calculations during the course of this work.

Note added in proof.—R. H. Miller and R. Sherr have found approximately 10 percent K-capture in Na^{22} (reported at the Rochester meeting of the A.P.S., June, 1953). Consequently the γ-ray efficiency for 511-kev radiation in Fig. 4 should be increased 10 percent. [With this correction the 600-kev point (Cs^{134}) is in good agreement with the other data]. This correction of Fig. 4 changes the number of 723-kev quanta per positron to 1.05 ± 0.08, but has negligible effect on the intensity of the 1033-kev γ ray.

[25] E. P. Wigner, Phys. Rev. **56**, 519 (1939); Lecture Notes, University of Wisconsin, 1951 (unpublished).
[26] G. L. Trigg, Phys. Rev. **86**, 506 (1952).
[27] O. Kofoed-Hansen and A. Winther, Phys. Rev. **86**, 428 (1952).
[28] R. Nataf and R. Bouchez, Phys. Rev. **87**, 155 (1952).
[29] S. A. Moszkowski, Phys. Rev. **82**, 118 (1951).
[30] Dewan, Pepper, Allen, and Almquist, Phys. Rev. **86**, 416 (1952).
[31] Wu, Rustad, Perez-Mendez, and Lidofsky, Phys. Rev. **87**, 1140 (1952).
[32] E. J. Konopinski and L. M. Langer, *Reviews of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 261. This excellent review article gives additional references not listed here and contains a detailed discussion of the evidence for the various interactions obtained from forbidden β spectra.
[33] J. M. Blatt, Phys. Rev. **89**, 83 (1953).