

previously.¹ The ft value for the 1835-keV transition is 3275 ± 75 sec (calculated with the NBS tables²). A specific search was made for a ground-state transition (see Fig. 1), but no evidence was found, the percent branching being less than 0.3 percent (corresponding to $\log ft$ greater than 7.3).

In general, for allowed transitions, the equation

$$A = ft \left(\left| \int 1 \right|^2 + R \left| \int \sigma \right|^2 \right) \quad (1)$$

is valid, where $R = g_{GT}^2/g_F^2$ and $A = 2\pi^3 \hbar^7 \ln 2/m^5 c^4 g_F^2$ are constants. R and A are related to the constants B and x introduced by Kofoed-Hansen and Winther³ as follows:

$$A = B/(1-x); \quad R = x/(1-x). \quad (2)$$

The 1835-keV O^{14} decay is a $0+ \rightarrow 0+$ transition,⁴ i.e., a pure Fermi transition, so Eq. (1) reduces to $A = ft |\int 1|^2$. Hence one of the beta-decay constants g_F may be determined directly provided the nuclear matrix element $|\int 1|^2$ is known.

In terms of the isotopic spin quantum numbers T and T_z ,⁵

$$\left| \int 1 \right|^2 = T(T+1) - T_z T_z'. \quad (3)$$

For the $O^{14} - N^{14} - C^{14}$ triplet $T=1$, $T_z = -1, 0$, and 1 , respectively, and $|\int 1|^2 = 2$. It is of critical importance to realize that this calculation of the matrix element depends solely on the assumption of charge independence of nuclear forces, an assumption common to all determinations of nuclear matrix elements. It does not, however, require any further assumption about nuclear structure such as is needed to calculate the Gamow-Teller matrix element. There is very considerable experimental evidence for the validity of charge independence, especially in the low-lying levels of light nuclei. Radicati⁶ and, more recently, MacDonald⁷ have calculated the effects of Coulomb forces and configuration interactions in mixing nuclear states. Their findings indicate that for O^{14} these effects should have only an extremely small effect on the value of $|\int 1|^2$.

In view of these facts, it is assumed here that no uncertainty will be introduced in an evaluation of A because of the nuclear matrix element. Thus $A = 6550 \pm 150$ sec and $g_F = 1.374 \pm 0.016 \times 10^{-49}$ erg cm³. This *direct* determination of the Fermi coupling constant is in reasonable agreement with the various attempts which have previously been made to derive it indirectly from shell-model analyses of allowed decays.^{3,8}

Though the Fermi matrix element $|\int 1|^2$ can be computed with a high degree of certainty, the calculation of the Gamow-Teller matrix element $|\int \sigma|^2$ is at present most uncertain. The neutron decay ($|\int 1|^2 = 1$; $|\int \sigma|^2 = 3$), and none other, provides a case where the

calculation of $|\int \sigma|^2$ is well founded and almost certainly correct. With the reported ft value for the neutron⁹ and the value of A determined from the O^{14} decay, $R = 1.37_{-0.30}^{+0.40}$. Almost the entire uncertainty in R is introduced by the large uncertainty in the neutron half-life.

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

² *Tables for the Analysis of Beta Spectra*, National Bureau of Standards Applied Mathematics Series, No. 13 (U. S. Government Printing Office, Washington, 1952).

³ O. Kofoed-Hansen and A. Winther, Phys. Rev. **86**, 428 (1952).

⁴ R. Sherr and J. B. Gerhart, Phys. Rev. **91**, 909 (1953).

⁵ E. P. Wigner, Phys. Rev. **56**, 519 (1939).

⁶ L. A. Radicati, Proc. Phys. Soc. (London) **A66**, 139 (1953).

⁷ W. M. MacDonald, doctoral dissertation, Princeton University, 1954 (unpublished).

⁸ See sources cited in reference 4.

⁹ J. M. Robson, Phys. Rev. **83**, 349 (1951).

Tensor Forces and the β Decay of C^{14} and O^{14}

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THE surprisingly long lifetime¹ ($\log ft = 9.03$) of the C^{14} β decay has been known for a long time to be unexplained either by the supermultiplet theory nor by the jj -coupling shell model. Some authors suggested that this high ft value could be explained in intermediate coupling by an "accidental" cancellation of the matrix element involved. Inglis² showed that such a cancellation could not occur within a pure p^{-2} configuration if one takes into account central forces and ordinary spin-orbit interaction. Inglis' consideration holds also for a mutual spin-orbit interaction of the type $V_{12} = (\mathbf{s}_1 + \mathbf{s}_2) \cdot \mathbf{l}_{12} V(r_{12})$, as in this case the relevant non-vanishing matrix elements of $\sum V_{ij}$ arise only from the interaction of the holes with closed shells, which is an ordinary (single-nucleon) spin-orbit interaction.

We would like to point out that such a cancellation can occur if tensor forces are also considered. In the following, an interaction

$$H = \frac{1}{2}(1+P)[V_c e^{-r/r_c}/(r/r_c) + S_{12} V_t e^{-r/r_t}/(r/r_t)] \quad (1)$$

is assumed between the two p holes, and each hole has also a spin orbit interaction $a(\mathbf{l} \cdot \mathbf{s})$ with the residual

nucleus (a is positive for a hole). P is the Majorana exchange operator: $S_{12} = 3(\sigma_1 \cdot r_{12})(\sigma_2 \cdot r_{12})/r_{12}^2 - (\sigma_1 \cdot \sigma_2)$. Harmonic oscillator wave functions are used. The parameter of the well is adjusted so that the mean square radius for the s^4p^{10} configuration be $(3/5)^{1/2} \times 1.2 \times 10^{-13} A^{1/2}$ cm. The energy matrix for the states p^{-2} , $(J, T) = (0, 1)$ of C^{14} is found to be,³ in the LS coupling

$$\begin{array}{c} {}^3S_1 \\ {}^1P_1 \\ {}^3D_1 \end{array} \begin{array}{c} \begin{array}{ccc} {}^3S_1 & {}^1P_1 & {}^3D_1 \\ \hline (5/4)(I_0+I_2) - (3/2)I_1 & a(2/3)^{1/2} & (3/\sqrt{5})J_1 - (\sqrt{5})J_2 \\ a(2/3)^{1/2} & 0 & -\frac{1}{2}a(10/3)^{1/2} \\ (3/\sqrt{5})J_1 - (\sqrt{5})J_2 & -\frac{1}{2}a(10/3)^{1/2} & \frac{1}{2}(I_0+I_2) - J_2 - \frac{3}{2}a \end{array} \end{array}, \quad (3)$$

where the I and J are the harmonic oscillator radial integrals⁴ for the potentials $V_e e^{-r/r_e}/(r/r_e)$ and $V_t e^{-r/r_t}/(r/r_t)$, respectively. These matrices can be diagonalized and determine the wave functions

$$x\psi({}^1S_0) + y\psi({}^3P_0)$$

and

$$\alpha\psi({}^3S_1) + \beta\psi({}^1P_1) + \gamma\psi({}^3D_1)$$

of the ground states of C^{14} and N^{14} . The nuclear β -decay matrix element of the Gamow-Teller operator (the Fermi operator does not contribute) between the states considered is found to be

$$\left| \int \sigma \right|^2 = 6(x\alpha - y\beta/\sqrt{3})^2. \quad (4)$$

The experimental ft value suggests that (4) is vanishingly small. x and y are both of the same sign,² and (4) can vanish only if α and β are of the same sign; this can be achieved only if the $({}^3S_1, {}^3D_1)$ matrix element in (3) is large enough (α and β are of opposite signs if this matrix element is zero²), which requires a strong tensor force of short range (so that J_2 be small as compared to J_1).

Such a force can be obtained for example by inserting in (1) the following numerical data⁵ which fit also the ground-state data of the deuteron: $r_e = r_t = 1.185 \times 10^{-13}$ cm, $V_e = 7.9$ Mev, $V_t = 79.6$ Mev. If then a is adjusted to the value $a = 2.3$ Mev, (4) practically vanishes, the wave functions being $0.65\psi({}^1S_0) + 0.76\psi({}^3P_0)$ for C^{14} , and $0.264\psi({}^3S_1) + 0.374\psi({}^1P_1) + 0.89\psi({}^3D_1)$ for N^{14} . The value of the magnetic moment of N^{14} computed with this wave function is 0.38, in reasonable agreement with the experimental value⁶ of 0.40368. The quadrupole moment of N^{14} is given by

$$Q = [-(1/5)\beta^2 + (7/50)\gamma^2 + (4\sqrt{5}/25)\alpha\gamma] \langle r^2 \rangle. \quad (5)$$

The value obtained with this wave function is $Q = 0.011$ barn, in good agreement with the experimental value⁷ of 0.01. It should be pointed out that the interaction adopted represents a rather extreme case of a large tensor force compared to the central forces. Moreover,

scheme,

$$\begin{array}{c} {}^1S_0 \\ {}^3P_0 \end{array} \begin{array}{c} \begin{array}{cc} {}^1S_0 & {}^3P_0 \\ \hline (5/4)(I_0+I_2) - (3/2)I_1 & -a\sqrt{2} \\ -a\sqrt{2} & -a \end{array} \end{array}, \quad (2)$$

and the energy matrix for the states p^{-2} , $(J, T) = (1, 0)$ of N^{14} is³

the positions of the energy levels of the excited states computed with the same interaction are unsatisfactory; particularly, the 3D_2 level is lowered by the tensor force down to 0.15 Mev below the lowest ($J=1$) level.⁸ Thus, it is clear that this model (in which configuration interaction has not been considered) should not be considered as giving a satisfactory explanation. It is, however, interesting to see that tensor forces can play an important role in a possible cancellation of the matrix element (4).

Some indication that the long lifetime of C^{14} is actually caused by an accidental cancellation of the matrix element has been recently found in measurements of the lifetime of the β decay of O^{14} to the ground state of N^{14} (the mirror transition to that of C^{14}). Penning and Schmidt⁹ found a 3 percent branching ratio for this decay of O^{14} and quote the value $\log ft = 6.7$; more accurate measurements by Gerhart¹⁰ yield a branching ratio not more than 0.3 percent, and $\log ft$ value greater than 7.3. This suggests that in this case the cancellation is partly removed due to the deformation of the wave function of the $(J, T) = (0, 1)$ state caused by the additional Coulomb forces present in O^{14} . When this additional Coulomb force is taken into account as a perturbation $-e^2/r$ of the interaction (1) between the two p holes, the matrix element (4) instead of being zero, becomes

$$\left| \int \sigma \right|^2 = 6[\langle {}^1S_0 | e^2/r | {}^1S_0 \rangle - \langle {}^3P_0 | e^2/r | {}^3P_0 \rangle] / (E' - E)^2 x^2 \alpha^2, \quad (6)$$

where E' and E are the excitation energies of the two p^{-2} , $(J, T) = (0, 1)$ states of C^{14} . $E' - E$ is of the order of magnitude of the experimental first excitation energy¹ of C^{14} , 4.1 Mev, or probably up to twice as much. Using¹¹

$$ft = 5300 / \left| \int \sigma \right|^2, \quad (7)$$

one finds, for O^{14} , $\log ft \sim 7.1$, up to 7.7, in fair agreement with the experimental results.

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¹ F. Ajzenberg and T. Lauritsen, *Revs. Modern Phys.* **24**, 321 (1952).

² D. R. Inglis, *Revs. Modern Phys.* **25**, 390 (1953).

³ I. Talmi, *Phys. Rev.* **89**, 1065 (1953).

⁴ I. Talmi, *Helv. Phys. Acta* **25**, 185 (1952).

⁵ H. Feshbach and J. Schwinger, *Phys. Rev.* **84**, 194 (1951).

⁶ W. G. Proctor and F. C. Yu, *Phys. Rev.* **77**, 716 (1950).

⁷ J. Sheridan and W. Gordy, *Phys. Rev.* **79**, 513 (1950).

⁸ This result is in agreement with results independently obtained by T. Regge, *Nuovo cimento* **11**, 285 (1954).

⁹ J. R. Penning and F. H. Schmidt, *Phys. Rev.* **94**, 779 (1954).

¹⁰ J. B. Gerhart, preceding Letter [*Phys. Rev.* **95**, 288 (1954)].

¹¹ A. Winther and O. Kofoed-Hansen, *Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd.* **27**, 14 (1953).

Magnetic Moment of Os¹⁸⁹†

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A NUCLEAR induction signal of Os¹⁸⁹ with a width of 10 gauss, measured between the minima of the differentiated dispersion mode, has been detected in molten OsO₄. The liquid phase of this particular compound was chosen because the Os¹⁸⁹ nucleus has a large electric quadrupole moment, $Q = (+2.0 \pm 0.8) \times 10^{-24}$ cm²,¹ and it is therefore necessary to place the nucleus in a symmetric molecular configuration in order to minimize interactions which broaden the resonance line. It is presumed that in our sample, the osmium nucleus is located at the centroid of a tetrahedron having oxygen atoms at its vertices.

The resonant frequency was compared to that of Cl³⁵ in pure TiCl₄ with the result

$$\nu(\text{Os}^{189})/\nu(\text{Cl}^{35}) = 0.791896 \pm 0.000093. \quad (1)$$

With the spin of Os¹⁸⁹ assumed to be 3/2,¹ and with the known values of the frequency ratios $\nu(\text{Cl}^{35})$ in TiCl₄/ $\nu(\text{Cl}^{35})$ in RbCl,² $\nu(\text{Cl}^{35})$ in RbCl/ $\nu(\text{H}^2)$,³ $\nu(\text{H}^2)/\nu(\text{H}^1)$,⁴ the value of the magnetic moment was found to be, with $\mu(\text{H}^1) = 2.79268$,⁵

$$\mu(\text{Os}^{189}) = +0.650655 \pm 0.000081 \text{ nm}. \quad (2)$$

The positive sign in (2) was verified by comparing the sign of the Os¹⁸⁹ signal with that of O¹⁷ in the same compound. Sign comparisons were also made with H² and N¹⁴. The earlier determination of $\mu(\text{Os}^{189}) = +0.70 \pm 0.09$ nm by Murakawa and Suwa¹ is in agreement with the sign and the more precise value of Eq. (2).

In view of the fact that the single-particle shell model⁶ predicts that, for the case of a positive magnetic moment, only $p_{1/2}$, $f_{5/2}$, and $h_{9/2}$ states are available between the magic numbers 82 and 126, it seemed to us of interest to check the previous spin determination by an independent method. Accordingly, the heights h and line widths ΔH of Os¹⁸⁹ and Cl³⁷ signals were compared.

The reference Cl³⁷ signal from a 7.10 molar LiCl solution containing 0.0075 molar Mn(NO₃)₂ was used, and care was taken to ascertain that both line shapes represented the nonsaturated slow passage case. If the frequency, the rf field intensity, the Q of the receiver coil, the filling factor, and the sweep field remain unchanged for the measurements of both signals, the application of the phenomenological equations⁷ gives

$$I(\text{Os})[I(\text{Os})+1] = I(\text{Cl})[I(\text{Cl})+1] \\ \times \frac{h(\text{Os})}{h(\text{Cl})} \frac{N(\text{Cl})}{N(\text{Os})} \frac{\gamma(\text{Cl})}{\gamma(\text{Os})} \left(\frac{\Delta H(\text{Os})}{\Delta H(\text{Cl})} \right)^2. \quad (3)$$

With the known value of 3/2 for $I(\text{Cl})$,⁸ the measured values of the number of nuclei N in each sample, and our experimental results for the other ratios, we find

$$I(\text{Os}^{189}) = 1.45 \pm 0.13, \quad (4)$$

thus verifying the value 3/2.

Signals were not observable in solidified OsO₄ or in powdered Os metal which has a crystal structure of hexagonal symmetry, presumably because of an unfavorable ratio T_2/T_1 .

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¹ K. Murakawa and S. Suwa, *Phys. Rev.* **87**, 1048 (1952).

² C. D. Jeffries, *Phys. Rev.* **92**, 1262 (1953).

³ Walchli, Leyshon, and Scheitlin, *Phys. Rev.* **85**, 922 (1952).

⁴ G. Lindström, *Arkiv Fysik* **4**, 1 (1951).

⁵ Sommer, Thomas, and Hipple, *Phys. Rev.* **82**, 697 (1952).

⁶ M. G. Mayer, *Phys. Rev.* **78**, 16 (1950); P. F. A. Klinkenberg, *Revs. Modern Phys.* **24**, 63 (1952).

⁷ F. Bloch, *Phys. Rev.* **70**, 460 (1946).

⁸ Townes, Holden, Bardeen, and Merritt, *Phys. Rev.* **71**, 644 (1947).

Experimental Study of the μ^- Meson Mass and the Vacuum Polarization in Mesonic Atoms*

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STUDIES of the x-rays emitted in transitions of mesons between atomic orbits about nuclei have been extended¹ to $3D-2P$ and $4F-3D$ transitions in a variety of elements for both π^- and μ^- mesons. Particular attention has been paid to μ^- mesonic transitions having energies below 90 keV, using thin filters between the anticoincidence counter and the NaI crystal of the scintillation spectrometer.² Because of the large and rapid change in absorption cross section at the photoelectric "K edge" energy and the precise knowledge of