Assuming isotropic angular distribution of the secondary disintegration products with respect to the He^5 at rest, this continuum would present a plateau on the numbers *vs.* range curve between these limits. Our observations serve to indicate such a plateau by the dip in the numbers curve at 6 cm range. The experimentally allowable minimum range is not sufficiently small to enable a search for the corresponding decrease at small range. The evidence for the existence of this continuum is partially vitiated by uncertainty as to the exact distribution of particles in the background from (1).

Further evidence for the validity of our hypothesis arises from the extended width of the "homogeneous" alpha-particle group of 7.10 cm range as compared to the homogeneous alpha-particle group of 12.4 cm range from reaction (2). If we assume the shape of the underlying continuum due to (1) as extending horizontally to intercept the vertical portion of the total curve and attribute the residue to reaction (4), we find the width at half-maximum of the resultant peak is 6 mm. The half-width at half-maximum is thus 1 mm greater than is observed in the simple reaction (2).

This additional width corresponds to a variation in energy of 0.07 Mev and applying the uncertainty principle one calculates the mean life of He^5 to be approximately 6×10^{-20} sec.

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On the Comparison of Proton-Proton and Proton-Neutron Interactions

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Based on the data of Tuve, Heydenburg and Hafstad for the scattering of protons by protons and that of Amaldi and Fermi for the scattering of neutrons by protons a comparison of the two interactions is made. The present comparison is made more accurately than previously and allows for the uncertainty in the chemical factor C which is used in the interpretation of the neutron-proton experiments. The results are substantially in agreement with those of Breit, Condon and Present, the two interactions being very nearly equal. A slight excess of neutron-proton attraction over that between protons is indicated by the present calculation. Fermi's conclusion that the singlet S level of deuterium is virtual is reexamined by taking into account the effect of the range of force and of the chemical factor on the mean life of neutrons in an atmosphere of protons. Experiment agrees better with a virtual than with a real level. Nevertheless the evidence for its virtual character is not so good as to exclude completely the possibility that it is real. Tests by means of which a real level could be found if present are discussed.

A COMPARISON of the proton-proton and proton-neutron singlet S interactions using the experiments of Tuve, Heydenburg, Hafstad[1] on protons and of Amaldi, Fermi[2] on neutrons has already been made.[3] This comparison was not as complete as is desirable because: (a) Only Fermi's conclusion[4] that the lowest proton-

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[1] M. A. Tuve, N. P. Heydenburg and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).

[2] E. Amaldi and E. Fermi, Ricerca Scient. **7** *I*, 310 (1936); E. Amaldi and E. Fermi, Phys. Rev. **50**, 899 (1936).

[3] G. Breit, E. U. Condon and R. D. Present, Phys. Rev. **50**, 825 (1936).

[4] E. Fermi, Ricerca Scient. **7** *II*, 13 (1936). The extension of Fermi's formula used here is obtained by calculating without approximations, the transition probability due to

neutron singlet S level is virtual was used, and (b) only one value of Fermi's chemical factor was taken into account. This incompleteness is overcome in Table I, wherein we give values obtained for the proton-neutron interaction using the Amaldi-Fermi thermal neutron elastic scattering cross section of 43×10^{-24} cm^2. According to Fermi,[4] this experimental value should be set equal to $C(\pi a_1^2+3\pi a_3^2)$, where a_1 and a_3 are respectively the values in cm of the intercepts of straight line portions of the singlet and triplet wave functions for zero energy on the axis representing the distance between proton and neutron, while C is the chemical factor which would be 4 for very tight chemical binding of the hydrogen atoms. Fermi estimated $C=3.3$, while Bethe[5] has estimated that in paraffin C might be as low as 2.5. In the calculations a_3 was obtained using the empirical deuteron binding energy. The values tabulated correspond to 2.14 Mev for this energy. A change of this to 2.18 Mev makes no appreciable difference in the results below. In the calculations we used the newer values $e=4.8036\times 10^{-10}$ e.s.u., $c=2.9986\times 10^{10}$ cm/sec., $m=0.9115\times 10^{-27}$ g, $h=6.638\times 10^{-27}$ g cm^2/sec. These differ somewhat from the values used in the previous calculations on proton-proton scattering. The possible errors in the latter resulting from the change in units have been estimated and found to be within the experimental error with the exception of the Mev. The unit of depth of the potential well in Table I is 1.0080 Mev in terms of the newer units and is the same as that used in making the proton-proton calculations; to distinguish it from the Mev unit the depths D carry a prime. The values $(D_1)_{\pi\nu}'$ are the depths in 1.0080 Mev of the proton-neutron interaction in the singlet S state; $(D_1{}^c)_{\pi\pi}'$ are the corresponding depths of the proton-proton interaction acting in addition to the Coulombian repulsion. It is seen from this table that within the reasonable range of values of r the proton-neutron interaction is slightly greater than the proton-proton interaction if the ^1S level is virtual and is appreciably greater if that level is real.

TABLE I. *Values of proton-proton and proton-neutron well depths.*

r (mc^2/e^2)	$\frac{1}{2}$	1	2	3	C	SINGLET LEVEL
$(D_1)_{\pi\nu}'$	48.2	11.3	2.48	0.94	3.3	Virtual
	54.6	14.7	4.49	2.86	3.3	Real
	48.7	11.6	2.60	1.02	2.5	Virtual
	54.1	14.4	4.17	2.32	2.5	Real
$(D_1{}^c)_{\pi\pi}'$	48.7	11.1	2.42	0.98		

The revised comparison of energies of isobaric nuclei made by Feenberg and Wigner[6] and later by Feenberg and Phillips[7] and by Wigner[8] shows that a change of a neutron into a proton increases the energy of a nucleus somewhat more than would be expected from the Coulomb energy alone. This indicates that the attraction between two protons is weaker than that between two neutrons by more than merely the Coulomb energy. Similarly the values of Table I indicate a relatively stronger attraction between a proton and a neutron than between a proton and a proton.

By a slight extension of Fermi's formula[4] for the mean life τ of a neutron one finds:

$$\frac{1}{\tau}=\frac{128\pi^5 n}{h}\left(\frac{\nu}{c\alpha_3}\right)^3(\mu_p-\mu_n)^2\frac{D_3+E_3'}{D_3(1+\alpha_3 r)}\times\left(\frac{D_3-D_1}{D_3+E_3'-D_1}\right)^2[1+\alpha_3(r+a_1)]^2.$$

Here n = number of hydrogen atoms per cm^3, ν = frequency of emitted radiation, D_1 and D_3 are respectively the depths of square potential wells in singlet and triplet states, E_3' = energy of deuteron $\cong -2.14$ Mev, μ_p and μ_n are the respective magnetic moments of proton and neutron, r = radius of potential well, $\alpha_3=(-ME_3'/\hbar^2)^{+\frac{1}{2}}$. Using $n=7.8\times 10^{22}$ cm^{-3}, $(\mu_p-\mu_n)=5.01\ e\hbar/2Mc$, $E_3'=-2.14$ Mev, and other units as in the comparison of proton-proton and proton-neutron depths, one obtains Table II.

From Fermi's theory, Amaldi and Fermi[2] conclude that $10^4\tau=1.7$ sec. experimentally. This value agrees best with the numbers obtained

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magnetic dipole radiation for an interaction potential represented by a square well. The accurate value of the integral of the product of initial and final functions is used. If $r\rightarrow 0$ Fermi's formula is obtained as a limiting case of the one used here.

[5] H. A. Bethe, private communication.

[6] E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937).

[7] E. Feenberg and M. Phillips, Phys. Rev. **51**, 597 (1937); especially reference 9 on p. 604.

[8] E. Wigner, Phys. Rev. **51**, 947 (1937); reference 11.

above for a virtual level and for $C=2.5$. An increase in the range of force from 0 to 1 or 2 times e^2/mc^2 is seen to improve the agreement slightly. However this agreement is not necessarily strong evidence for concluding that the level is virtual because: (a) Fermi's theory for the interpretation of the *albedo* may not be sufficiently accurate, as has been pointed out by Halpern, Lueneburg and Clark.[9] According to them a 50 percent or 100 percent correction may have to be applied to the experimental value. An increase in τ of 100 percent would spoil the agreement with a virtual level for $C=2.5$ without giving good agreement with a real level, although it would leave the agreement with a virtual level about the same for $C=3.3$. (b) There may be other processes besides the emission of magnetic dipole radiation which would involve the absorption of neutrons. The τ due to magnetic dipole radiation alone would then be larger than the experimental value; this might agree better with a real ${}^1S$ level. (c) It is assumed in the calculation of the capture cross section that the magnetic moments of proton and neutron have constant values unaffected by the mutual proximity of the particles. A partial justification of this assumption can be given as follows. The magnetic field at the proton due to the neutron is of the order μ_n/r^3, where r is the distance between proton and neutron. The proton, pictured as a small electrically charged sphere, will begin to spin about its axis when brought into this field with the frequency $\omega\sim e\mu_n/Mcr^3$. M here is the mass of the proton. The magnetic moment resulting from this precession is $\sim\omega e r_p^2/c=\Delta\mu_p$, where $r_p=$proton radius. The ratio of the induced magnetic moment to the original is $\Delta\mu_p/\mu_p\sim(\mu_n/\mu_p)(e^2/Mc^2r)\sim m/M$. Although on this basis no serious correction to the moments of elementary particles should be expected inside nuclei, the essentially classical picture above may not be sufficiently good.

In view of the present disagreements between theory and experiment it will perhaps be worth while to have some way of testing whether the ${}^1S$ level of the deuteron is real or virtual. One method available for this purpose is that of Teller.[10] It may also be possible to detect a real singlet level by excitation using bombardment with heavy particles, measuring their absorption as a function of velocity or else perhaps determining their energy loss directly.

TABLE II. *Values of $10^4\tau$; $\tau=$mean life in seconds.*

r (mc^2/e^2)	0	$\frac{1}{2}$	1	2	C	SINGLET LEVEL
$10^4\tau$	2.77	2.72	2.67	2.62	3.3	Virtual
	7.2	8.6	10.7	20.7	3.3	Real
	2.14	2.09	2.04	1.94	2.5	Virtual
	4.8	5.5	6.4	9.8	2.5	Real

Still another possibility is offered by the selective absorption of γ-rays. For a band of γ-rays having a width $\Delta\nu$ considerably greater than the natural breadth of the absorption line and an average frequency ν, the effective collision cross section due to magnetic dipole absorption from a stable ${}^3S$ state to a stable ${}^1S$ state is

$$\sigma=\frac{8\pi^3\nu}{3ch\Delta\nu}(\mu_p-\mu_n)^2\left(\int_0^\infty 4\pi u_1u_3dr\right)^2$$

$$\cong 2.64\times10^{-28}\frac{\nu}{\Delta\nu}\left(\int_0^\infty 4\pi u_1u_3dr\right)^2 \text{cm}^2.$$

Here u_1/r and u_3/r are respectively the radial wave functions for singlet and triplet states, normalized so that $\int_0^\infty 4\pi u^2dr=1$. For square wells of radius r one obtains

$$\left(\int_0^\infty 4\pi u_1u_3dr\right)^2=\frac{4(E_1'E_3')^{\frac{1}{2}}}{[(-E_1')^{\frac{1}{2}}+(-E_3')^{\frac{1}{2}}]^2}$$

$$\times\frac{(D_1+E_1')(D_3+E_3')(D_1-D_3)^2}{(1+\alpha_1r)(1+\alpha_3r)D_1D_3(D_1+E_1'-D_3-E_3')^2}.$$

The notation is the same as in the formula for $1/\tau$. The second factor in this formula is nearly unity for short range forces, so that $\sigma\cong1.6(\nu/\Delta\nu)\times10^{-28}$ cm² if $E_1'=-0.10$ Mev. In pure deuterium the absorption cross section for 2 Mev radiation due to the Compton effect is $\sim1.5\times10^{-25}$ cm². In order that the nuclear absorption be at least as great as the electronic it is thus necessary that $(\nu/\Delta\nu)\sim1000$, or that the γ-ray band be no more than 2000 volts wide. This band would

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[9] O. Halpern, R. Lueneburg and O. Clark, Phys. Rev. **51**, 775 (1937).

[10] J. Schwinger and E. Teller, Phys. Rev. **51**, 775 (1937); E. Teller, Phys. Rev. **49**, 420 (1936).

have to be chosen so as to include the presumably 2.0 Mev absorption frequency. Such a source of γ-rays would probably be difficult to find, unless it should prove possible to use the radiation emitted in the transition ${}^1S \rightarrow {}^3S$ itself. This could be attempted by bombarding H^2 with H^1 or n^1. The energy of the bombarding particles would then have to be at least $4/3 \times 2$ Mev $= 2.7$ Mev, whereas if H^2 were bombarded with H^2 one would need at least 4 Mev incident particle energies. It would be interesting to know whether there are γ-rays emitted in such experiments that show selective absorption by H^2.

Note added in proof: Dr. R. D. Present has made the following comment in connection with the above note: "Assuming the level to be real and to be situated at about -125 kv and using $A_{\pi\pi}$ as determined from *THH* the discrepancy in He^4 obtained by Rarita and myself[11] would disappear because the range of forces would increase to the Feenberg-Share[12] value. Then all the experimental facts for the 2, 3, and 4-body problems would be consistent with the nuclear model, with the possible exception of the Coulomb energy of He^3 which would return to Share's[13] value approximately. This would tend to support the conclusion mentioned in your paper that $A_{\pi\pi} < A_{\pi\nu}$." In connection with Dr. Present's comment it is of interest to note that Westcott[14] using an independent set of experiments reaches the same conclusion concerning the mean life of neutrons as Fermi reaches. Westcott's method depends essentially on the use of boron as a standard absorber and is thus rather independent of complicated calculations on the diffusion of neutrons. It appears therefore that one is faced with a dilemma between the calculations of Rarita and Present with the above comment of Present on the one hand and the measurements on the mean life of slow neutrons on the other. The easiest solution of this apparent contradiction would be to suppose that the questionable point (c) in the application of standard theory to the calculation of τ is of importance and that, therefore, the magnetic moments of the proton and neutron in their free state do not give the correct result for the calculation of the mean life. Theoretical considerations by Willis E. Lamb on how this might come about from the point of view of the electron neutrino theory, which we have seen in manuscript, will appear shortly in the *Physical Review.*

We are indebted to the Alumni Research Foundation of the University of Wisconsin for a grant.

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[11] W. Rarita and R. D. Present, Phys. Rev. **51**, 788 (1937).

[12] E. Feenberg and S. Share, Phys. Rev. **50**, 253 (1936).

[13] S. Share, Phys. Rev. **50**, 488 (1936).

[14] C. H. Westcott, Proc. Camb. Phil. Soc. **33**, 122 (1937).