10^6, we obtain

$$g_J(^2S_{\frac{1}{2}}, H)/g_I = 658.2163,$$

where g_I is the proton g value measured in oil. After applying the relativistic correction, $g_S/g_I = 658.2280$. The probable error of this result from statistical sources alone is about 0.0004. The stated result may, however, be subject to systematic errors of unknown magnitude, presumably arising from effects associated with any inhomogeneity of the magnetic field. We believe that an upper limit to the total uncertainty is about ± 0.0030.

Gardner and Purcell give

$$2g_L/g_I = 657.475 \pm 0.008.$$

A combination of the two results yields

$$g_S/g_L = 2(1.001145 \pm 0.000013).$$

Theoretical calculations of this quantity have been carried out to second order by Schwinger,[6] and more recently to fourth order by Karplus and Kroll.[7] The result is

$$g_S/g_L = 2[1+(\alpha/2\pi) - 2.973\alpha^2/\pi^2] = 2(1.0011454).$$

The rather startling agreement of experiment and theory can only be considered fortuitous at this point, in view of the experimental uncertainties. However, even in their present state the results give very strong evidence of the validity of the higher order quantum electrodynamical calculations. This work is being continued to increase the precision with which g_S/g_I is known.

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The Electron-Neutron Interaction*

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THE existence of a weak attractive interaction between electrons and neutrons has recently been reported by two groups of workers.[1,2] It was immediately recognized that such an interaction is to be expected on the basis of current meson theories of nuclear forces as a consequence of the partial dissociation of a neutron into a proton and virtual negative meson. Explicit calculations[3] have shown that an electron-neutron interaction of the required character and order of magnitude is indeed obtained on the basis of this assumption.

We wish to show first that an electron-neutron interaction of the desired character and magnitude can also be obtained as a direct consequence of attributing to a neutron an anomalous magnetic moment in the manner suggested by Pauli[4] without any further assumptions. The relativistic (one-particle) hamiltonian for such a neutron in an external electromagnetic field is

$$H = \beta M + \boldsymbol{\alpha}\cdot\mathbf{p} - \mu_N(e/2M)[\beta\boldsymbol{\sigma}\cdot\mathbf{H} - i\beta\boldsymbol{\alpha}\cdot\mathbf{E}],$$

where μ_N is the magnetic moment of the neutron measured in nuclear magnetons. On reducing this by a canonical transformation to the corresponding nonrelativistic hamiltonian by the method of Foldy and Wouthuysen[5] one obtains

$$H = \beta M + (\beta p^2/2M) - \mu_N(e/4M^2)\beta\,\mathrm{div}\mathbf{E} + \mu_N(e/4M^2)\beta\boldsymbol{\sigma}\cdot[\mathbf{p}\times\mathbf{E} - \mathbf{E}\times\mathbf{p}],$$

where we have retained terms up to order $(1/M)^2$. For the coulomb field of an electron located at the point $\mathbf{x}_e$, the above hamiltonian becomes

$$H = \beta M + (\beta p^2/2M) + 4\pi\mu_N(e^2\beta/4M^2)\delta(\mathbf{x}-\mathbf{x}_e) + \cdots.$$

The term[6] containing the delta-function $\delta(\mathbf{x}-\mathbf{x}_e)$ is exactly of the form of the electron-neutron interaction. Expressing the interaction in terms of the well-depth V_0 of an equivalent[7] square well of radius e^2/mc^2, one obtains for V_0

$$V_0 = \pi\mu_N(e^2/M^2)[(4\pi/3)(e^2/mc^2)^3]^{-1} = \tfrac{3}{4}\mu_N(\hbar c/e^2)^2(m/M)^2\, mc^2 = 3900 \text{ ev},$$

where we have taken $\mu_N = -1.9$ nuclear magnetons. The above figure is to be compared with the experimental value:[2] $V_0 = 5300 \pm 1000$ ev.

We do not wish to imply that this is the correct explanation of the interaction, but we do wish to point out an important bearing of the above result on meson-theory calculations of the interaction. When one calculates the electromagnetic properties of nucleons according to meson theory by canonical transformations which remove the coupling of the mesons to the nucleon to any given order in the meson coupling constants, one obtains interaction terms representing the anomalous magnetic moment of the nucleon interacting with the magnetic field, together with its relativistic complement expressing the interaction of an electric dipole moment for the nucleon with the electric field, plus an additional term which gives rise to a direct electron-neutron interaction. In the calculations employing this method (Case, and Borowitz and Kohn) only the last term has been compared with the experimental interaction. Actually, the electric dipole moment term gives in second order an additional contribution which is exactly that found above[8] and which must be added to the direct term before the comparison with experiment is made. In the calculations performed by direct computation of neutron scattering by an external coulomb field (Slotnick and Heitler, and Dancoff and Drell) the extra term is automatically included in the computation. We believe that this extra term may account for the discrepancy between the results of Slotnick and Heitler and of Borowitz and Kohn which was noted in a footnote to the paper of the latter authors.

* Supported by the AEC.

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6 Note the similarity of origin of this term with the "Darwin" term for the hydrogen atom as derived in reference 5.

7 By the equivalent square well is meant here one having the same volume integral for the potential and consequently giving the same scattering cross section in the Born approximation at very low energies.

8 In this respect we disagree with the remarks of K. M. Case given at the beginning of Sec. VI of his paper referred to in footnote 3 above. A careful investigation is necessary before discarding terms proportional to the Dirac matrix $\boldsymbol{\alpha}$ on the grounds that they are velocity proportional, since they may give rise to velocity independent contributions in higher order.

4.4-Minute Radiations from Zr^{89}

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THE recent findings of Shure and Deutsch[1] regarding 79.3-hour Zr^{89} have been confirmed in this laboratory employing a 180° magnetic spectrometer. The sources were 1-mil foils of zirconium which had been irradiated by means of the probe method[2] in the 22-Mev betatron here. Our results indicate a simple positron spectrum with an allowed shape (at least to 450 kev, where the unfavorable source thickness is apparent), having a Kurie end point at 890 ± 10 kev, and in addition a single K-conversion line at 896 ± 5 kev.[3] The presence of the corresponding gamma-ray was established also by means of a scintillation spectrometer. The ratio of conversion electrons to positrons is 0.023. Deutsch[4] has obtained a conversion coefficient of 8×10^{-3} for this transition and, in addition, has measured the half-life of the excited state in Y^{89}, thought to be involved, to be 13 seconds. From these two values, together with the energy, he has designated the transition as being magnetic 2^4-pole. Goldhaber[5] has made an independent determination of approximately 16 seconds for this half-life.

The assignment by Deutsch is consistent with the shell theory of Mayer.[6] The measured spin[6,7] of Y^{89} (39 protons) in its ground state is $\frac{1}{2}$, and also is consistent with Mayer's scheme, which would put the odd proton in a $p_{\frac{1}{2}}$ state with odd parity. Similarly, the first excited state is obtained by putting this proton in a $g_{9/2}$ subshell with even parity. This fixes the gamma-transition to be magnetic 2^4-pole, in agreement with the above assignment. In the case of Zr^{89} (49 neutrons) we are concerned with a similar competition between the $g_{9/2}$ and the $p_{\frac{1}{2}}$ subshells for the odd neutron. It is probable from the results of Deutsch and Goldhaber that the 890-kev positron group proceeds from the ground state of Zr^{89} to the excited state (913±5 kev upon adding the K binding energy) of Y^{89}. Thus, if we assume a $p_{\frac{1}{2}}$ state for Zr^{89} the positron group would have to be at least third forbidden. This is not consistent with the ft value of 1.3×10^6 seconds, found in the present investigation with the aid of the curves of Feenberg and Trigg;[8] rather, the transition is either allowed or first forbidden. Accordingly, it is reasonable to assume the levels of Zr^{89} to be inverted relative to Y^{89}, with the odd neutron in a $g_{9/2}$ (even parity) ground state, thus rendering the positron spectrum allowed.

In order to find additional support for this we have investigated the 5-minute isomeric transition in Zr^{89} extensively. The sources employed were formed by irradiation of zirconium foil with 21-Mev x-rays. The half-life was found to be 4.4±0.1 minutes, with less than 1 percent of detectable background present. This is in good agreement with the value of 4.5 minutes found by Dubridge and Marshall.[9] The energy of the gamma-ray was determined with a scintillation spectrometer, by comparison with annihilation radiation at 511 kev and Ba^{137} radiation at 661 kev, to be 588±5 kev. This was confirmed by measurements of the K-conversion line in a 180° spectrometer, which gave 590±5 kev for the gamma-ray energy. The total conversion coefficient was determined, employing the scintillation spectrometer and comparing with that of the 661-kev radiation of Ba^{137}, to be 0.07±0.02. The $K/(L+M)$ ratio was separately determined in the 180° spectrometer to be 7±2. From these the K-conversion coefficient was found to be 0.06±0.02. These results, together with the lifetime, indicate the transition is magnetic 2^4-pole. This is consistent with the assignment of $p_{\frac{1}{2}}$ to the isomeric state of Zr^{89}. Accordingly, one suspects the presence of an allowed positron group going to the ground state of Y^{89}, competing with the 588-kev transition to the ground state of Zr^{89}. Absorption, magnetic spectrometer, and scintillation spectrometer results indicate a weak positron group of approximately 2.5-Mev maximum energy present to the extent of 6 percent of the conversion electrons associated with the 588-kev transition. Since the half-life of these particles was found to be 5±1 minutes, this group was attributed to the expected transition between the metastable state of Zr^{89} and the ground state of Y^{89}. A suggested partial level scheme is shown in Fig. 1. The ft value of the high energy group is 7×10^6 seconds, a value which is of the same order of magnitude as the long-lived group at 890 kev.[10]

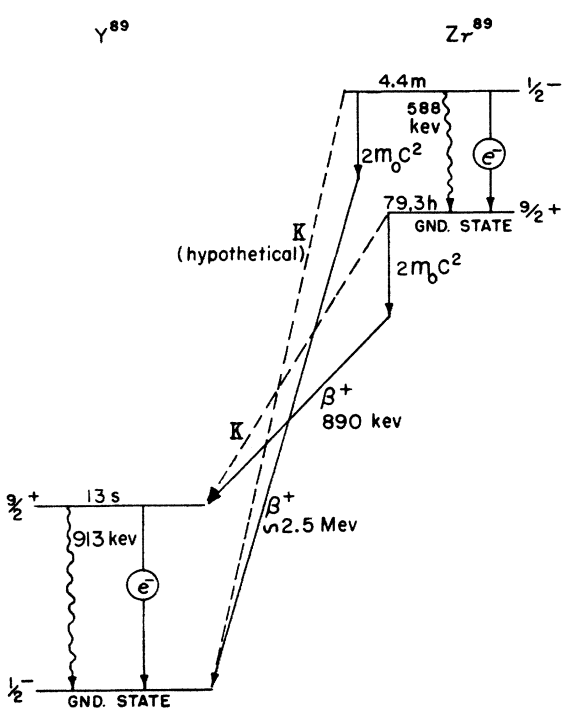

FIG. 1. Tentative partial level scheme for Zr^{89} and Y^{89}.

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The Ionization Loss of μ-Mesons at Relativistic Energies in Anthracene*

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THE development of scintillation counting techniques has made it possible to measure ionization energy losses of high energy charged particles which pass through a small thickness of material. This makes it feasible to check the validity of the density effect correction to the ionization loss formula which is predicted by several authors.[1-3] μ-mesons in the cosmic radiation at sea-level provide an ideal source of relativistic particles for such an experiment because a wide range of energies is available and absorption by radiation losses and by nuclear collisions is negligibly small.

The arrangement was similar in principle to the one described in a previous paper,[4] except that two identical scintillation crystals (3 cm in diameter and 3 cm long) were used, giving two independent measurements of the energy loss of any particular μ-meson. In order to investigate the ionization loss curve at relativistic energies, lead absorbers were used to determine three energy bands for μ-mesons from (a) 190 to 460 Mev, (b) 460 to 960 Mev, and (c) higher than 960 Mev. Coincidence $ABCD$ (Fig. 1) defines a narrow beam of particles which must traverse practically equal path-lengths through both crystals. Trays E, F, and G cover the solid angle defined by $ABCD$. Counters H detect events accompanied by side showers, which are eliminated from the analysis. According to our knowledge of the energy spectrum of single electrons at sea-level, they should all be stopped in the first 12.7 cm of lead, and, therefore, do not reach tray E. Only events in which the master coincidence $ABCD$ is accompanied by pulses from counters (a) $E-(F+G)$, (b) $EF-G$, or (c) EFG are