Letters to the Editor

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Exchange Forces between Neutrons and Protons, and Fermi's Theory

FERMI[1] has recently developed a successful theory of β-radioactivity, based on the assumption that transmutations of a neutron into a proton and vice versa are possible and are accompanied by the birth or disappearance of an electron and a neutrino.

This theory implies the possibility of deducing the exchange forces between neutrons and protons, introduced more or less phenomenologically by Heisenberg. (This idea occurred also quite independently to my friend, D. Iwanenko, with whom I have since had the opportunity of discussing the question.) Consider two heavy particles a and b, a being in a neutron and b in a proton state. If a becomes a proton and b a neutron the energy remains unchanged. Now these two degenerate states of the system may be linked up by a two-step process: the emission of an electron and a neutrino by the neutron a which becomes a proton, and the ensuing re-absorption of these light particles by the proton b which becomes a neutron. The energy of the system will be in general not conserved in the intermediate state (compare the theory of dispersion). The emission and re-absorption of a positron and neutrino may also take place[2]. In this way the two degenerate states of the system considered are split into two energy states, differing by the sign of the exchange energy.

Since the rôle of the light particles (ψ-field) providing an interaction between heavy particles corresponds exactly to the rôle of the photons (electromagnetic field), providing an interaction between electrons, we may adapt for our purposes the methods used in quantum electrodynamics to deduce the expression for Coulomb forces.

Putting $\psi = \psi_0 + g\psi_1 + g^2\psi_2 + \ldots .$, where g is the Fermi constant ($\sim 4 \times 10^{-50}$ erg. cm.^{3}), and using the theory of perturbations and retaining only that part of ψ which corresponds to the absence of light particles in the initial and final states, we obtain

$$\left(H_0 - i\hbar\frac{\partial}{\partial t}\right)\psi_2 \sim \left(K \mp \frac{1}{16\pi^3\hbar c r^5} I(r)\right)\psi_0,$$

where K is an infinite constant, r is the distance between a and b and $I(r)$ is a decreasing function of r, which is equal to 1 when $r \ll \hbar/mc$ (m is the mass of the electron). Neglecting K, one would obtain the same result if one introduced directly in the wave equation of the heavy particles an exchange energy $A(r)$:

$$A(r) = \pm\frac{g^2}{16\pi^3\hbar c r^5} I(r),$$

the sign of $A(r)$ depending on the symmetry of ψ in respect to a and b. Introducing the values of $\hbar$, c and g, we obtain

$$|A(r)| \ll 10^{-85}\, r^{-5} \text{ erg.}$$

Thus $A(r)$ is far too small to account for the known interaction of neutrons and protons at distances of the order of $r \sim 10^{-13}$ cm.

If the difference of masses of the neutron and of the proton is larger than the sum of the masses of an electron and a neutrino, the emission of light particles by a heavy particle may take place without violation of the conservation of energy. But again the corresponding value of the exchange energy may be shown to be far too small

$$|A(r)| < g^2\left(\frac{mc}{\hbar}\right)^3 \sim 10^{-18} \text{ erg.}$$

Our negative result indicates that either the Fermi theory needs substantial modification (no simple one seems to alter the results materially), or that the origin of the forces between neutrons and protons does not lie, as would appear from the original suggestion of Heisenberg, in their transmutations, considered in detail by Fermi.

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[1] Fermi, *Z. Phys.*, **88**, 161; 1934.

[2] Wick, *Rend. R. Nat. Acad. Lincei*, **19**, 319; 1934.

Interaction of Neutrons and Protons

As electrons and positrons are expelled in some reactions from nuclei, we can try to treat these *light* particles like the photons emitted by atoms. Then the interaction of *heavy* particles (protons, neutrons) can be considered as taking place *via* light particles described by the equations of a ψ-field in the same manner as electromagnetic, for example, Coulomb, interaction takes place through an electromagnetic field, or photons.

The *first* order effects are the expulsion (or absorption) of an electron, which case was treated recently by Fermi, or of a positron. We may remark that the application of Fermi's formalism to positron disintegration of light nuclei (which we get by changing the sign of the charge number and taking for the latter the appropriate value) gives results which fit, though not very accurately, the observed relation between the half-period and the maximum energy of the disintegration particle[1]. Though there seems to be a quantitative disagreement between Fermi's theory (applied to positrons) and positron disintegration, on the other hand the calculated values for K and Rb support Fermi's assumption of the existence of quadripole transitions of heavy particles, giving too big values for the half periods in comparison with the usual dipole disintegrations. The exceptional position of K and Rb is in some way rather *anschaulich*. We may remark that the Sargent-Fermi rule, in contrast to the Geiger-Nuttall law, shows a less pronounced dependence on the charge number, so that for qualitative considerations even the wave functions of free particles can be used.

The *second* order effects give specially the probability of production of pairs, which is in the case of the ψ-field less effective than in the electromagnetic case, as the charge, e, is much bigger than Fermi's coefficient, g (the 'charge' for the ψ-field). The most important second order effect is the subsequent production and annihilation of an electron and positron, in the field of proton and neutron,