nation of the 41-hour period and the 14.5-hour period. The 1.7-hour period might well correspond with the 2.4-hour period observed by the author.

The Production of V^{52}

Vanadium when bombarded with deuterons or slow neutrons becomes strongly radioactive, emitting negative electrons and gamma-rays. The same isotope is formed in each case, namely V^{52} (half-life 3.9 ± 0.1 m) according to the reactions,

$$V^{51}+H^2\rightarrow V^{52}+H^1;\quad V^{52}\rightarrow Cr^{52}+e^-$$
$$V^{51}+n^1\rightarrow V^{52}+\gamma.$$

This has been confirmed by producing the same isotope by bombarding chromium and manganese with fast neutrons. In each case the decay curves show the presence of an isotope whose half-life is 3.9 ± 0.1 minutes. V^{52} is accordingly produced in the reactions

$$Cr^{52}+n^1\rightarrow V^{52}+H^1$$
$$Mn^{55}+n^1\rightarrow V^{52}+He^4.$$

Decay curves illustrating these reactions are shown in Fig. 11.

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Note on the Interaction Between Nuclei and Electromagnetic Radiation

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The exchange character of nuclear forces makes it impossible to formulate in a consistent way the coupling between the electromagnetic field and a nucleus described by a model which involves only heavy particles. This difficulty does not occur in a theory which introduces light particles as carriers of the charge in the exchange processes. The actual contribution of these light particles to the transition probabilities is proved to be negligible in the limit of wavelengths of the radiation large compared with nuclear dimensions and nonrelativistic motion of the heavy particles. In this limit one is justified in taking as coupling term $-(\mathbf{ED})$, where $\mathbf{D}$ is the dipole moment calculated from the heavy particle model, and $\mathbf{E}$ is the electric field. A marked influence of the exchange processes on the radiation properties of the nucleus exists even in the limit considered.

For the treatment of the nucleus as a mechanical system, it is considered as built up solely of protons and neutrons. To get agreement with the observed mass defects of light nuclei, one has to assume the interaction forces between these heavy particles to be of finite range and to be—at least partly—exchange forces. One would like to use this model also for calculating probabilities of emission and absorption of gamma radiation. Here, however, a serious difficulty appears, as Condon and Breit have pointed out.[1] It is not possible to justify any specific form of the interaction between nuclei and radiation from the heavy particle model only. In fact, because of the exchange processes implied by the

[1] E. U. Condon and G. Breit, Phys. Rev. **49**, 904 (1936).

model, the charge of a heavy particle varies with time. If, for instance, there are Majorana forces acting between the heavy particles the Hamilton function of the nucleus contains terms exchanging spin and charge of two particles.[2] This means physically that a heavy particle in a nucleus does not always remain a proton, respectively neutron, but changes its charge and is sometimes a proton, sometimes a neutron. If now the interaction with the electromagnetic field is to be consistent with Maxwell's equations, one has to define the currents so as to satisfy the equation of continuity. There must then be currents flowing at points of space where there are no heavy particles. The motion of the charge is therefore not described completely by the motion of the heavy particles. On the other hand, the validity of the equation of continuity does not determine the form of the interaction, for this equation enables us to define only the curl-free part of the current. In the interaction with a light wave, however, the contribution of the curl-free part of the current vanishes because div $\mathbf{A}=0$. It is therefore not possible to define a current from the heavy particle model alone which can be used to find the interaction of nuclei with radiation. This difficulty does not occur if one tries to explain the mechanism of the exchange by that suggested in Fermi's theory of the β-decay. Although this theory has not succeeded so far in giving a satisfactory explanation of nuclear binding forces we want to use it here to illustrate the situation assuming that the general features will remain in any theory in which the exchange is explained by the creation and reabsorption of light particles. There the electric current and density are given by the ordinary expressions for the electron current and proton current and satisfy the equation of continuity. Having thus a reasonable definition of the current density $\mathbf{i}$ one may use as interaction the common form $-(1/c)\int \mathbf{Ai}d\tau$. From this basis we want to consider the limiting case of nonrelativistic velocities of the heavy particles and wave-lengths of the radiation large compared with nuclear dimensions. This limit is realized rather well in the photoelectric disintegration of the deuteron. In this case Condon and Breit took as interaction $-(\mathbf{ED})$, where $\mathbf{D}$ is the electric dipole moment of the heavy particles relative to the center of gravity, as given by the heavy particle model. This procedure is plausible for the following reason: Though one meets difficulties in defining a current in the heavy particle model, one can reasonably define the charge density and therefore the electric dipole moment. It then seems plausible to take $-(\mathbf{ED})$ as interaction for emission and absorption of radiation of long wave-lengths, by analogy with systems in which there are no exchange forces. To justify this assumption we notice that for long wave-lengths on the basis of Maxwell's theory the interaction is $-\mathbf{E}(\mathbf{D}_h+\mathbf{D}_l)$,[3] where $\mathbf{D}_h$ and $\mathbf{D}_l$ are the dipole moments of the protons and electrons, respectively. The error which one incurs in taking $\mathbf{D}_h$ from the heavy particle model and neglecting $\mathbf{D}_l$ altogether is certainly smaller than $-(\mathbf{ED}_l)$. What one neglects is in fact the possibility of finding, in the deuteron, the neutron split into proton and electron; or in terms of the Fermi theory, one neglects those parts of the wave function which represent states with electrons present. The relative order of the error will therefore be given by the probability of finding an electron in the nucleus. To estimate this roughly one may introduce an "exchange frequency" which will be of the order I/h, where I is the average potential energy. One may further suppose that during an exchange process the electron exists on the average for approximately the time a/c. Here a is the range of nuclear forces, and c is the velocity of light, since the exchange electrons move practically with light velocity. The probability of finding an electron is then $(I/h)(a/c)$.[4] Since I is of the

[2] The description of Majorana forces as an exchange of positional coordinates is equivalent to this on account of the Pauli principle.

[3] For long wave-length $-(1/c)\int \mathbf{Ai}d\tau = -(\mathbf{A}/c)\int \mathbf{i}d\tau = -(\mathbf{A}/c)\int \mathbf{r}\dot{\rho}d\tau$ by partial integration using the equation of continuity. This is equal to $-(1/c)(\mathbf{A}\dot{\mathbf{D}})$ which gives in the resonance case $-(\mathbf{ED})$.

[4] The connection with the Fermi theory is given by the following consideration. Suppose one would be able to calculate the exchange forces between neutron and proton by a perturbation method, taking the Fermi operator as perturbation. One might start with a wave packet for the neutron and proton as wave function in zeroth approximation. In first approximation wave functions would occur which represent states with two protons and one electron and neutrino present. If one has chosen the right function as zeroth approximation, the energy perturbation due to these parts of the wave function will represent the main

order of the average kinetic energy of the heavy particles $mv^2/2$ one has $Ia/hc \sim (mva/h)\cdot(v/c)$. The first factor is of order one. The neglected term therefore contains a factor v/c and its neglect is justified in the nonrelativistic limit.

The meaning of Condon and Breit's approximation is thus that one considers the exchange as a sudden change in the dipole moment, and neglects the retardation of the forces between heavy particles. One has by no means neglected the exchange itself. The influence of the exchange processes in our limit is evident from the following considerations. We take as interaction $-(\mathbf{E}\mathbf{D}_h) = -\mathbf{E}\sum_\mu e\rho_\mu \mathbf{r}_\mu \cdot \rho_\mu$ is the character variable of the μth particle, with the eigenvalues 0 and 1 corresponding to neutron and proton. $\mathbf{r}_\mu$ is the coordinate relative to the center of gravity. Due to the exchange processes the ρ_μ are not constants of motion. If for instance the Hamilton function of the heavy particles contains a Majorana term

$$\tfrac{1}{2}\sum_{\mu\nu} I(r_{\mu\nu})\Omega_{\mu\nu}$$

one has

$$\dot{\rho}_\mu = (i/\hbar)\sum_{\mu\nu} I(r_{\mu\nu})(\rho_\nu - \rho_\mu)\Omega_{\mu\nu}.$$

Here $\Omega_{\mu\nu}$ is an operator which exchanges charge and spin of two particles μ and ν if they are of different charge and is zero otherwise. I is a function of their relative distance $r_{\mu\nu}$. It is this time-dependence of the ρ_μ which makes the sum of oscillator strengths

$$\sum_l f_{0l} = (2m/\hbar^2)\sum_l (E_l - E_0)\,|D_{0l}|^2$$

differ from its value for ordinary forces[5] as soon as exchange forces are involved. The summation gives

$$(\hbar/i)(m/\hbar^2)(D\dot{D} - \dot{D}D)_{00},$$

where

$$\dot{D} = \sum_\mu \rho_\mu \dot{x}_\mu + \dot{\rho}_\mu x_\mu.$$

From this one obtains

$$\sum_l f_{0l} = Z\left(1-\frac{Z}{A}\right) - \frac{1}{2}\frac{m}{\hbar^2}\Big(\sum_{\mu\nu}(x_\mu - x_\nu)^2 F(r_{\mu\nu})\Omega_{\mu\nu}\Big)_{00}$$

$$= Z\left(1-\frac{Z}{A}\right) - \frac{1}{2}\frac{m}{\hbar^2}A(A-1) \times ((x_1-x_2)^2 F(r_{12})\Omega_{12})_{00},$$

where the second term comes from the part $\sum \dot{\rho}_\mu x_\mu$. If one assumes that the energy of a nucleus does not depend strongly on the shape of the potential hole F, one gets as an estimate of the magnitude of the extra term

$$(m/\hbar^2)\cdot(a^2/4)\cdot E_p,$$

where a is the range of nuclear forces, and E_p is the total potential energy of the nucleus. The extra term can thus become of the same order as the first term. This means that the exchange processes have a marked influence on radiation properties of the nucleus even in the limit considered here in which the details of its mechanism do not essentially enter into consideration.

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part of the potential energy of the deuteron. The probability of finding the system in one of the higher states β is given by

$$P = \sum_\beta |F_{\beta 0}|^2/(E_\beta - E_0)^2,$$

where F is the Fermi operator. For those states which contribute essentially to the binding $E_\beta - E_0 \sim (\hbar c/a)$, since the wave-lengths of the electron and the neutrino must be of the order of the range a of the exchange forces. Then P is of the order

$$\frac{a}{\hbar c}\sum_\beta \frac{|F_{\beta 0}|^2}{E_\beta - E_0} \sim \frac{aI}{\hbar c}.$$

[5] This was noticed by E. Feenberg, Phys. Rev. **49**, 328 (1936).