separation r there is on the average a time element τ characterizing a probable transition. Recombination depends on the chance that the ions are within r cm of each other for a time t sufficiently large compared to τ to insure transition. At a value of $r=r_0$ where τ is such that say 90 percent or more encounters result in transition we can then roughly fix the limiting collision radius.

In our present ignorance we can certainly set r_0 as greater than the kinetic theory diameter of the ion, and it may well be 10 times as large. One may then apply these considerations to the ionosphere. At 100 km Humphreys[3] gives the pressure as 0.0067 mm and the temperature of the order of 55 or more below °C. I will use $-73°\text{C}$. On this basis ϵ for $(O_2)_2^+$ will be 4.24×10^{-3} and $\alpha=1.61\times10^{-8}$. For the same gas $\alpha_r=\pi r_0^2(c_+^2+c_-^2)^{\frac{1}{2}}$ with $r_0=4\times10^{-8}$ and 4×10^{-7} cm, respectively, gives $\alpha_r=2\times10^{-10}$ and $\alpha_r=2\times10^{-8}$ *independent of the pressure*. Thus in the ionosphere unless $r_0>4\times10^{-7}$ cm the Thomson theory still applies.

Where electrical data from the ionosphere indicate values of α of the order of 10^{-10} one might assume that the recombination was no longer ionic but electronic.[4] This question can readily be answered if the oxygen content of the ionosphere is known. The work of Bradbury[5] gives the chance of electron attachment to O_2 molecules for a given electron energy. The ions once formed are stable. From the rate of ionization, the rate of electron attachment and the coefficient of recombination of ions the relative concentrations of the ions and electrons can be determined. If, as auroral spectra show, appreciable O_2 is present in the ionosphere it is probable that the negative carriers are largely ions.

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[1] L. B. Loeb, Phys. Rev. **51**, 1110 (1937).

[2] J. J. Thomson, *Conduction of Electricity Through Gases*, third edition. Vol. I pp. 40–47. L. B. Loeb, *Kinetic Theory of Gases*, second edition p. 592.

[3] W. J. Humphreys, *Physics of the Air*, second edition p. 70.

[4] C. Kenty, Phys. Rev. **32**, 624 (1928). F. Mahler, Bull. Am. Phys. Soc. **12**, abstract 55, p. 16 (1937).

[5] N. E. Bradbury, Phys. Rev. **44**, 885 (1933).

Evidence for the Simultaneous Ejection of Three Neutrons from Elements Bombarded with Fast Neutrons

It has recently been shown[1] that most elements when bombarded by very fast neutrons yield radioactive isotopes corresponding to the ejection from the stable nucleus of one neutron in addition to the bombarding particle. It now appears that in certain cases the impinging neutron can eject two neutrons in addition to itself. This phenomenon is best shown in the case of scandium.

The stable isotopes in this part of the periodic table are shown in Table I. Also included in this table are certain of the known radioactive isotopes. Scandium possesses normally a single stable isotope of mass number 45. When radiated by the fast neutrons (10 to 20 Mev) from lithium, which is bombarded by 6 Mev deuterons, scandium becomes strongly radioactive. Chemical separation of the bombarded specimen shows that there are two radioactive periods both positive in sign in the scandium precipitate. These half-life periods are approximately 4 hours and 52 hours and are in agreement with the results of Walke[2] who identified the same scandium isotopes by bombarding calcium with deuterons and potassium with alpha-particles.

TABLE I. *Stable and radioactive isotopes in the vicinity of scandium.*

	38	39	40	41	42	43	44	45	46
K	10 m	93%	.01%	7%	16 h				
Ca			97%		.7%	.1%	.2%	2.4 h	
Sc				53 m	4.1 h	4.0 h	52 h	100%	>a
Ti									8.5%

The reactions are then as follows:

$$\left.\begin{array}{ll} {}_{21}\text{Sc}^{45}+n\rightarrow{}_{21}\text{Sc}^{44}+n+n & \\ {}_{21}\text{Sc}^{44}\rightarrow{}_{20}\text{Ca}^{44}+{}_{+1}e & \text{(52 hr.)} \end{array}\right\} \quad \text{(A)}$$

$$\left.\begin{array}{ll} {}_{21}\text{Sc}^{45}+n\rightarrow{}_{21}\text{Sc}^{43}+n+n+n & \\ {}_{21}\text{Sc}^{43}\rightarrow{}_{20}\text{Ca}^{43}+{}_{+1}e & \text{(4 hr.)} \end{array}\right\} \quad \text{(B)}$$

Although there is no previously known case where three neutrons are ejected from an excited nucleus, such a process is not inconsistent with the recent consideration of excited nuclei proposed by Bohr.

When scandium is bombarded by neutrons of energy under 8 Mev neither the 4 hour nor the 52 hour period is observed. In addition to these periods in scandium, fast neutron bombardment always yields by the emission of an alpha-particle the 16 hour activity in potassium attributed to isotope K^{42}.

Among other elements that might show this phenomenon of multiple neutron ejection are copper and fluorine. In both cases there is evidence that the process occurs but the identification cannot be made as certain as in the case of scandium. The periods in fluorine corresponding to the ejection of two and three neutrons (i.e., F^{18} and F^{17}) are 108 min. and 1.2 min., respectively. The similar isotopes in copper are Cu^{62} and Cu^{61} with half-life periods of 10 min. and 3.5 hr. The 3.5 hour period of Cu^{61} is very weak compared to the strong 12.5 hour period of Cu^{64}.

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[1] Pool, Cork and Thornton, Phys. Rev. **51**, 890 (1937).

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On the Existence of Heavy Electrons

Different observers[1] believe they have found evidence for the existence of charged particles whose mass amounts probably to about fifty times the electron mass. Furthermore these particles seem to behave according to the Bethe-Heitler theory.[2]

The writer wishes to call attention to an explanation of the nuclear forces, given as early as 1934, by Yukawa,[3] which predicts particles of this sort.

Independently of Yukawa the writer arrived at the same conclusion: Kemmer has shown recently[4] that the formal conception of field theory proposed by the author[5] leads to great difficulties, if the proposed interaction energies have singular character. Interaction energies of nonsingular character can most easily be introduced by assuming the existence of some tensor field differing from that of ordinary radiation.

We describe *matter* by a 16 component spinor ψ, whose first four components refer to the *electron state*, the second four functions to the *neutrino state*, the third group to the *proton state* and the last four components to the *neutron state of matter*. Each of these states is defined by the values of a set of four indices (*charge numbers*) $(\alpha, \beta, \gamma, \delta)$ which have respectively the values $(1, 0, 0, 1)$, $(0, 1, 0, 1)$, $(1, 0, 1, 0)$ and $(0, 1, 1, 0)$. Quantum theory associates *particles* with this field which we denote by the same symbol ψ. They have the spin 1/2 and obey Fermi *statistics*. Their *antiparticles* are to be described as holes according to Dirac's idea and designated by $-\psi$. They have the same charge numbers as the particles but with reversed sign. If e represents the elementary charge $e\alpha$ is the *electric charge* of the particle in the state given by $\psi(\alpha, \beta, \gamma, \delta)$. $\gamma = 1$ or 0 indicates whether the particle has *heavy mass* (~ 2000) or light mass (~ 0 to 1). Matter satisfies evidently the relation $\alpha+\beta=\gamma+\delta=1$. The indices β and δ can be called *neutrino charge* and *light mass number*.

The known form of radiation is described by a tensor field A of four components (the vector potential). We attribute to its particles (photons), designated analogously by $A(\alpha, \beta, \gamma, \delta)$ the charge numbers 0. Emission of a photon by matter is due to an interaction term proportional to $e\alpha$ and can be described by the reaction:

$$\psi(\alpha, \beta, \gamma, \delta) \rightarrow \psi(\alpha, \beta, \gamma, \delta) + A(0, 0, 0, 0). \tag{1}$$

The components of the A field satisfy Poisson's equation, the charge density being expressed by a suitably chosen generalized Dirac matrix $P = e\psi^{+}\Lambda\psi$ (cf. reference 5). We generalize Poisson's equation, introducing the fundamental length λ in the form:

$$\left(\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \Sigma\frac{1}{\lambda^2}\right)A = -P. \tag{2}$$

A is now a tensor of more than four components. Σ is a matrix operating on the tensor indices analogously to the way Dirac's matrices act on the spin indices of ψ. We assume for simplicity A to have five components. Furthermore let Σ be of such a form that the four first components which represent a four vector satisfy the ordinary Poisson equation ($\Sigma = 0$), while the fifth component (a scalar) satisfies Eq. (2) with $\Sigma = 1$. In a nonrelativistic approximation the four-vector part gives the Coulomb potential, while the scalar part gives a static interaction term between particles of the form $(fe^2/r)\exp(-r/\lambda)$. f is a numerical factor, depending on the choice of the Λ matrix. A suitable choice (see reference 5) of the generalized Dirac matrices Λ gives the electrostatic interaction between charged matter particles plus the Heisenberg, Majorana, Wigner and Bartlett interactions between heavy matter particles[6] and the different interactions between heavy and light matter particles (β-decay, etc.) discussed by the author. The Heisenberg interaction seems to demand a second order tensor field A.

The *particles* associated with this *generalized radiation* field have integer spins and obey Bose statistics. Those components for which $\Sigma \neq 0$ have a rest mass $m = hc/\lambda \neq 0$.

We generalize the *conservation law* of charge numbers expressed in Eq. (1): Then the A particle which appears in nuclear reactions has the charge numbers $(1, -1, 0, 0)$. Radiation satisfies evidently the relations $\alpha+\beta=\gamma+\delta=0$. *Antiparticles* have of course once more the charge numbers with reversed sign. There are naturally no antiphotons as the charge numbers of the four-vector field are identically 0. β^{+} decay can be written down as the result of two successive reactions:

$$\psi(1, 0, 1, 0) \rightarrow \psi'(0, 1, 1, 0) + A(1, -1, 0, 0), \tag{3}$$

$$A(1, -1, 0, 0) \rightarrow \psi''(1, 0, 0, 1) + (-\psi'''(0, 1, 0, 1)). \tag{4}$$

A proton ψ decomposes into a neutron ψ' and a positively charged *Bose electron* A, which in turn decomposes into an ordinary (positive) electron ψ'' and an antineutrino—ψ'''. As, even in the β-spectra of highest known energy ($24\ mc^2$), those Bose electrons have never been observed, their mass must be greater than 24 electron masses. Yukawa from other considerations estimates about fifty electron masses.

If the corresponding field component has scalar character, the Pauli-Weisskopf theory[7] can be applied. The interaction between this field and the four-vector field (electromagnetic field) leads to a formula differing but little from the Bethe-Heitler theory.[2]

It seems highly probable that Street and Stevenson, and Neddermeyer and Anderson [1] have actually discovered a *new elementary particle*, which has been prediced by theory.

This particle is unstable and can only be of secondary origin, its mass being greater than the sum of the masses of electron plus neutrino. There exist very probably also other particles for example: $A(0, 0, 1, -1)$.

It is interesting to note that we have a nonlinear field theory, the field having tensorial and spinorial components. The one set is generalized Maxwell equations (2), which are quadratic in the A's if the electromagnetic interaction is included in (2) and quadratic in the ψ's. The other set has the form of generalized Dirac equations, proposed by the author, and contains linear terms in ψ and bilinear ones in the ψ's and A's.

The writer is indebted to his colleagues Professor J. Weigle (Genève) and G. Wentzel (Zuerich)[8] for many a helpful discussion.

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[1] J. C. Street and E. C. Stevenson, Bull. Am. Phys. Soc. **12**, 13 (1937); S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **51**, 886 (1937).

[2] H. Bethe and W. Heitler, Proc. Roy. Soc. **A146**, 83 (1934).

[3] H. Yukawa, Proc. Phys. Math. Soc. Japan **17**, 48 (1937).

[4] N. Kemmer, Helv. Phys. Acta **10**, 47 (1937).

[5] E. C. G. Stueckelberg, Nature **137**, 1032 (1936); CR. de la Soc. phys. et sc. nat. Genève **53**, 64 (1936); Helv. Phys. Acta **9**, 389 and 533 (1936). The matrices Λ in this note are the Λ and the Ω matrices in the former theory. Instead of the conservation law of charge numbers the author introduced in these former publications a certain relationship between particles and their antiparticles.

[6] See, for example, the different publications of the Leipzig Institute: S. Fluegge, Zeits. f. Physik **105**, 522 (1937); H. Volz, Zeits. f. Physik **105**, 537 (1937); H. Euler, Zeits. f. Physik **105**, 553 (1937).

[7] W. Pauli and V. Weisskopf, Helv. Phys. Acta **7**, 709 (1934); W. Pauli, Ann. Inst. H. Poincaré p. 137 (1936).

[8] G. Wentzel, Zeits. f. Physik **104**, 34 (1936) has also introduced new particles, but he attributed to them a mass near that of the proton (Bose protons and Bose neutrons).