of neutrons, but a smaller number of positive protons and a certain number of negative ones. This will shift the stability-limits (in the plot $(A-Z)/Z$ against Z) somewhat upwards. Remembering that Heisenberg's stability-limits lie actually rather too low, it seems that the introduction of negative protons may make the agreement between the theory and experiment much better.

Another consequence of the introduction of negative protons is *the possibility of the existence of isomeric nuclei,* that is, nuclei with the same charge and mass but different internal structure. The difference between two such nuclei will be that one of them has a pair of oppositely charged protons while the other, instead of that, two neutrons. Although such isomeric nuclei may possess rather different energies and spins, the transformation of one of them into the other will be very improbable as it involves the simultaneous transformation of two particles.

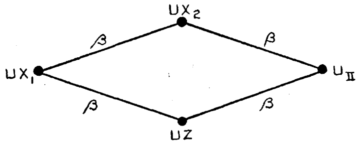

FIG. 1.

As a matter of fact we really have some indications of the existence of such isomeric nuclei. It seems at present rather certain that the radioactive element UZ, found by Hahn is the isomer of UX_2 according to the scheme of Fig. 1. From the observed energies of the emitted β-rays and from the considerations based on the application of the exclusion-principle for β-decay[3] we conclude that the intermediate nuclei UX_2 and UZ have different energies (energy-difference 1×10^6 v) and also different spins. This difference cannot be regarded as a simple excitation, because in that case there would be nothing to prevent UX_2 (which is the one with the greater energy) from transforming very rapidly ($\sim10^{-13}$ sec.) into UZ with the emission of a γ-ray. Actually UX_2 has a life of about one minute and then transforms into U_{II}. The above-mentioned idea of isomeric nuclei may, however, offer the explanation of the stability of UX_2 as regards its transformation into UZ. According to these lines of reasoning one must suppose that the disintegration $UX_1 \rightarrow UX_2+\beta^-$ is due to the transformation of a nuclear neutron into a positive proton and electron, while the disintegration $UX_1 \rightarrow UZ+\beta^-$ is due to the splitting of a negative proton into a neutron and electron (or the other way round).

It may be also remarked that the introduction of isomers may be of help for the removal of existing contradictions in the estimation of neutronic mass from different nuclear reactions.

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April 1, 1934.

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[3] G. Gamow, Proc. Roy. Soc. (in print).

Nature of the High Energy Particles of Penetrating Radiation and Status of Ionization and Radiation Formulae

(I) In this note it is desired in the first place to draw attention to some evidence for supposing that the high energy particles observed in Wilson-cloud photographs of penetrating radiation, have protonic mass. This evidence lies in the indications of a rather low value for the specific ionization by these particles. The most definite data in this respect are due to Kunze,[1] who observed the primary ionization produced by particles with $H\rho \sim 6\times10^6$. For this $H\rho$ the theoretical ionization by protons is very near the minimum value for particles with a single electronic charge, whilst that by electrons is about 70 percent greater.[2] Kunze's observations give a value practically equal to the minimum value. The results therefore indicate that these high energy particles are protons rather than electrons.[3] Remembering that the particles of lower $H\rho$, $\leq 10^6$, are nearly all electrons (from the investigations of Anderson, and Blackett and Occhialini) this would lead us to classify the ionizing particles of penetrating radiation into, (1) protons of high energy, and therefore possibly constituting the primary particles of penetrating radiation, (2) electrons of lower energy and of secondary origin.

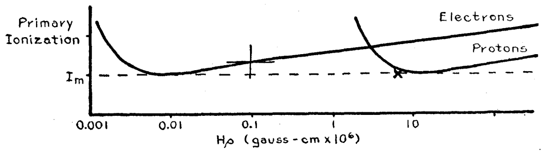

FIG. 1. +, observations requiring electronic mass; ×, observations requiring protonic mass.

Kunze's results require us to go even further than the assumption of protonic mass for the particles observed by him, because some of them have magnetic deflections corresponding to a negative charge. This would mean that *negative protons* exist, constituting, together with ordinary protons, the more energetic ionizing particles of penetrating radiation.

In view of these deductions it is desirable that more observations be made on the ionization and magnetic deflection of these high energy particles; also on the minimum ionization, I_m, which, from existing observations on ordinary β-particles, we have here taken to be 20 primary ions per cm in normal air. A disquieting feature of the

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[1] Kunze, Zeits. f. Physik **83**, 1 (1933).

[2] In their discussions of the ionization, Anderson, and Blackett and Occhialini, use formulae for the total energy loss. The energy loss is, however, not an exact measure of the specific ionization, and in the region of $H\rho$ considered here it gives an ionization for protons appreciably too high in comparison with electrons.

[3] A similar conclusion has been previously arrived at by the writer, using the same argument, but basing it on Skobelzyn's measurements of the total ionization (Phys. Rev. **42**, 881 (1932)).

existing measurements, insofar as the above interpretations are concerned, is that the region of $\mathrm{H}\rho$, for which Kunze gives his ionization results, is somewhat on the low velocity side of that which gives the minimum ionization by protons. For the above interpretation of his ionization measurements it is important that none of the particles concerned have a value of $\mathrm{H}\rho$ appreciably less than 6×10^6.

(II) Rossi's coincidence experiments, which show the existence of particles which can penetrate about one meter of lead, would give further support to the assumption that the high energy particles of penetrating radiation are protons, if the theories of radiative collisions, and of "pair-production" by photons, were applicable in the region of high energies. These theories set upper limits to the range of electrons and photons, which, in water, is about one meter, and in lead a few cm. Electrons or photons accordingly cannot be responsible for the coincidences in Rossi's experiments, nor can they be regarded as the primary particles of penetrating radiation. Protons, however, are not ruled out because, owing to their larger mass, their theoretical limiting range is $(1850)^2$ times the above values for electrons and photons.

The observations of Anderson[4] on the energy lost by electrons of energy $\sim3\times10^8$ volts, in traversing a lead plate, do not, however, fit easily with the theory of radiative collisions, upon which the argument of the preceding paragraph is based. Because of the large fluctuations in the theoretical radiative energy loss—the probability of an energy loss Q by an electron of energy T is proportional to T/Q—we cannot make a close comparison with existing data. If, however, the average energy loss recorded by Anderson is really a true average, it cannot be reconciled with the theoretical formulae. In view of this we consider in the next section the status of the radiative formula and also that of the ionization formula used in (I).

(III) The ionization formula has been previously considered by the writer.[5] Its derivation involves: (a) the relativistic expression for the field of a particle moving with uniform velocity, (b) the expression, $\mathbf{F}=(\mathbf{E}+[\mathbf{H}\cdot\mathbf{v}])e$ for the force acting on an electron in a given field, (c) non-relativistic quantum mechanics. (a) and (c) are well established, but we cannot be sure that (b) is correct if the external field varies appreciably in distances of the order of the electron radius, σ. These conditions, however, only exist in collisions with impact parameter $p\leqq\sigma\xi$, $\xi=(1-v^2/c^2)^{-\frac{1}{2}}$. Such collisions contribute an insignificant amount to the theoretical ionization by electrons with $\mathrm{H}\rho\sim10^7$. There is therefore no reason for doubting the ionization formula in the above discussion of Kunze's results.

Practically the same considerations apply to the formula of Heitler and Sauter[6] for the energy lost by an electron in radiative collisions with an atomic nucleus. C. F. v. Weiszäcker, and the writer, in calculations shortly to appear elsewhere, show that this formula may readily be derived by considering, in a system S' where the electron is initially at rest, the scattering by the electron of the harmonic components in the Fourier spectrum of the perturbing force due to the nucleus (which, in S', is the moving particle). The calculations show that practically all the radiative energy loss comes from the scattering of those components with frequencies $\sim mc^2/h$, and also that Heitler and Sauter's formula is largely free from the condition $Ze^2/hc\ll1$, which generally has to be satisfied in order that Born's approximation (used by H and S) may be valid. The formula accordingly only involves (a) and (b) as above—(b) because it is the Fourier spectrum of the force on the electron that must be considered in the above method and not that of the field at a point—, and the quantum-mechanical scattering formula (Klein-Nishina) for frequencies $\sim mc^2/h$. Of these, as in the case of the ionization formula, it is only (b) for collisions with $p\leqq\sigma\xi$, that is open to question. Such collisions are, however, relatively much more important for the radiative energy loss than for the ionization. Actually, under the conditions of Anderson's experiments, the maximum value of p for the radiative collisions (taking the shielding of the nucleus into account) is not of a different order of magnitude from $\sigma\xi$, so that in most of the radiative collisions the external force varies appreciably in distances of the order of the electron radius. A considerable decrease in the theoretical radiative effect may accordingly be achieved if we assume (b) to break down when $p\leqq\sigma\xi$. However, since the radiative effect depends on the Fourier components of low frequencies $\leqq mc^2/h\ll c/\sigma$, this breakdown must be supposed to concern not only the instantaneous force on the electron, but also its *time-integral* for a whole collision, which is difficult to understand.

Classically there is, of course, strong radiative reaction when $p\leqq\sigma\xi$, which considerably reduces the effective force on the electron. This effect is, however, unlikely to operate in quantum mechanics, in the way Swann[7] supposes it does. The large classical reaction in collisions lasting $<\sigma/c$ arises from the scattering of the Fourier components, in the field of the perturbing particle, of frequencies $>c/\sigma$. In actual collisions the intensity of these frequencies is so small that, in quantum mechanics, the probability that any one of them produces an effect, in a given collision, is vanishingly small. They cannot therefore hinder the action of the other components any more than the different frequencies in a weak beam of heterogeneous radiation affect each other.

In attempting to find some other reason, than the breakdown of (b), for the small energy loss observed by Anderson, the writer has considered the interference between the perturbations produced by the different nuclei when a fast electron traverses a solid. This, however, does not appreciably reduce the average effect.

In concluding I should like to express my indebtedness to Professor N. Bohr for many helpful discussions about the above questions. A more detailed treatment of those considered in (III) will appear elsewhere.

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April 16, 1934.

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[4] Anderson, Phys. Rev. **44**, 406 (1933).

[5] Williams, Proc. Roy. Soc. **A139**, 163 (1933).

[6] Heitler and Sauter, Nature **132**, 892 (1933).

[7] Swann, J. Frank. Inst. **217**, 59 (1934).