potentials enter explicitly in the density matrix, and lead to the existence of non-Maxwellian forces. With this definition of the dynamical operators, one has thus to abandon either Dirac's expression for the charge and current density or the validity of the conservation laws for energy and momentum. In particular one would not otherwise obtain consistent results, in computing on the one hand the induced charge density, and on the other the polarization energy, of the *epd* in an electrostatic field.

The simplest way of obviating these difficulties is to modify the density matrix in a way which does *not* depend on the electromagnetic field strengths present: i.e., to subtract from the operator given by the Dirac theory of the electron the expressions for the state of the electron distribution in the absence of external fields, for which all negative states are full. This procedure leads directly to the theory of the positron as we have developed it. On this theory one finds a polarization of a vacuum by an electromagnetic field which is infinite, and which can only be rendered reasonably unambiguous by special conventions about the way in which the divergent expressions occurring are to be handled.[2] This theory is therefore not only unable in general to predict the reaction of the *epd* to its own field, but can make no unambiguous statements about the fields induced by the *epd* under the influence of a given external field.

Nevertheless we believe that these difficulties in no way impair the limited validity of the theory of the positron, a validity which is limited to those questions which do not involve essentially the reaction of the electrons and positrons to their own radiation fields and thus does not extend to problems in which there are external fields whose frequency is of the order of the critical value mc^3/e^2. For at least insofar as the fields are themselves produced by electrons and positrons, the polarization of the *epd* manifests itself[3] in effects which are not unambiguously separable from the unknown effects of the radiation reaction of the particles. An instructive illustration of this may be found in the question of the fluctuations of the charge density of the *epd*, which was brought to our attention by Dr. Bloch. If we consider, for instance, the case of an empty *epd* in no external field, for which the expectation value of the charge density vanishes everywhere, we readily find that the expectation value of the square of the charge within any volume is infinite, corresponding to the fact that there are infinite fluctuations in the charge density. If we now ask in what measure it is possible to observe these fluctuations, we see that, to detect them, we must have an observing system (e.g., galvanometer) which will react in accordance with the electron-theoretic laws to electromagnetic fields of arbitrarily high frequency. If we admit that our instruments will not respond to waves of frequency large compared to mc^3/e^2, then we see at once that the *observed* fluctuations in the charge density will be finite and small, and that the paradoxical predictions of the theory of the positron are quite without physical consequences.

There exists the possibility, which is suggested by classical electron-theory, that we should have in the proton a particle which would respond in accordance with Maxwellian electrodynamic to waves of frequency far greater than mc^3/e^2, and that by its use the effects of the polarization of the *epd* could be separated from the problems of radiation reaction. There is, however, a growing mass of experimental evidence that so simple a theory of the proton can hardly be correct, and which lends support to the view that the present electrodynamics will be inapplicable in all questions involving lengths of the order of e^2/mc^2. From this point of view the paradoxes of the theory of the positron would be inextricably connected with those of quantum electrodynamics, and the applicability of the two theories would be similarly limited.

It must of course be remarked that the condition that in the field acting upon the charges there be no components of frequency of the order of mc^3/e^2 or greater is a sufficient, but by no means a necessary condition for the applicability of present electrodynamics, for this condition is clearly not relativistically invariant. The necessary condition, as Bohr particularly has emphasized, is that there exist a coordinate system in which such high frequency components are absent, insofar at least as one may consequently neglect the reaction of the charges to their own field. On the other hand, it is not in general possible to infer that, if in a given Lorentz frame high frequency components appear, the reaction of the charges to the low frequency components is correctly given by the Lorentz force. It is for this reason that one need not regard as altogether cogent the arguments recently advanced by v. Weizsaecker[4] for the validity of the theoretical formulae for the behavior of very high energy radiations in their passage through matter, formulae which are in fact very difficult indeed to reconcile with experiment.

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J. R. OPPENHEIMER

Pasadena,
June 2, 1934.

[2] Thus Peierls, to whom we are indebted for telling us of his results, has developed a method by which the polarization of the *epd* in an arbitrary electromagnetic may be computed in first order in a gauge and Lorentz invariant manner.

[3] W. H. Furry and J. R. Oppenheimer, Phys. Rev. **45**, 245 (1934); pages 261–2.

[4] L. F. v. Weizsaecker, Zeits f. Physik **88**, 612 (1934).

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A New Mode of Disintegration Induced by Neutrons

The capture of a neutron followed by the ejection of an α-particle is now a well-known process in the disintegration of light nuclei. Thus in nitrogen this may be written:

$$_7N^{14}+{}_0n^1={}_5B^{11}+{}_2He^4.$$

Using as a source of neutrons beryllium bombarded by 3 MV deutons, which were accelerated in the Lawrence-Livingston[1] apparatus, I have photographed six examples of a disintegration in which the emitted particle is of smaller charge than an α-particle and is probably a proton. The judgment is based on the character of the trace left

[1] E. O. Lawrence and M. S. Livingston, Phys. Rev. **45**, 608 (1934).

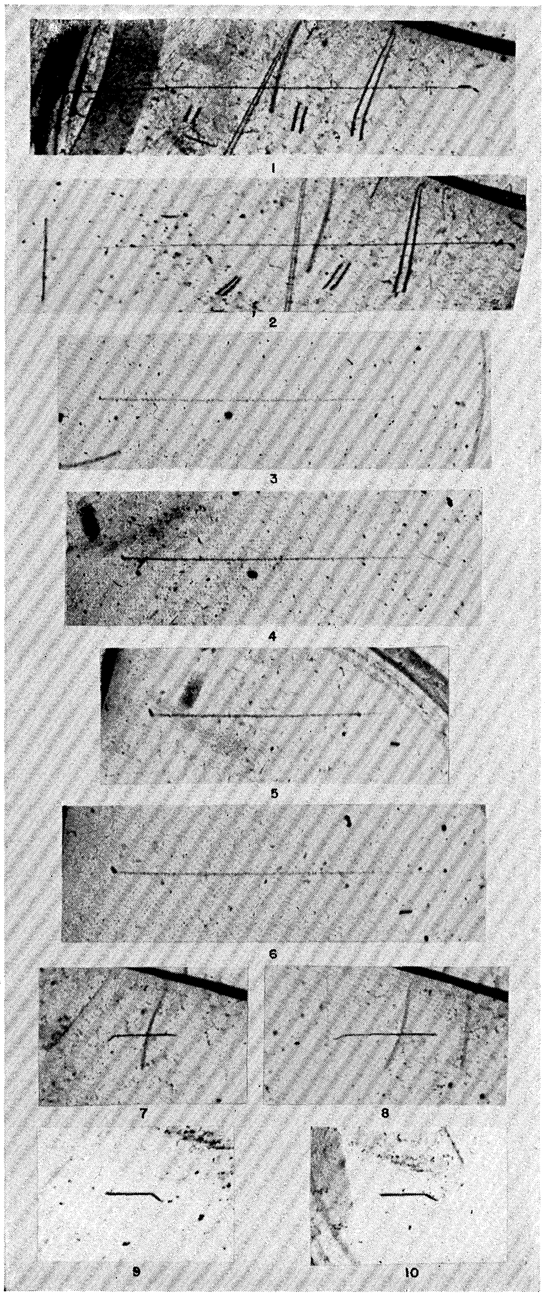

FIG. 1. Pairs of photographs of disintegration forks. Magnification about 0.6. 1, 2; 3, 4; 5, 6 are forks of the new type in which a proton is emitted instead of the usual α-particle. In 1, 2 the proton, proceeding from right to left hits the glass side wall of the chamber and in 3, 4 and 5, 6 the proton, proceeding from left to right, hits the floor of the chamber before reaching the end of its range. 7, 8; 9, 10 are pairs of photographs of the usual mode of disintegration. Attention is directed to the great difference in density of the short and long tracks in the first six pictures as compared to the last four.

in a Wilson cloud chamber by the disintegration, consisting of a short heavy track joined to a long thin track. The latter may equally well be a proton, a deuton or a nucleus of the newly discovered isotope of hydrogen ${}_1H^3$; but, since protons are known to exist in light nuclei and to emerge as such in many types of disintegration, we shall assume these particles to be protons.

To unravel the numerical relations in a disintegration fork one needs at least three facts; any three of the following will do: the lengths of the two tines, the angle between them and the direction of motion of the incident neutron. It is greatly to be desired that all four be known, for the fourth fact can be used as a check on the reaction chosen to represent the transmutation. Here we know only the length of the tine attributed to the nucleus and the angle between the two tines. Scattering in the iron which forms part of the apparatus used to accelerate the deutons introduces chaos in the directions from which the neutrons arrive at the cloud chamber. The evidence to distinguish these forks from the usual ones must be got from an examination of their photographs. Several of these are shown in Fig. 1 along with some of the ordinary type for comparison.

The cloud chamber contained both nitrogen and oxygen when the forks were photographed so that it is not possible to decide what reaction took place. Any of the following six may represent the fork:

$$
\begin{aligned}
{}_7N^{14}+{}_0n^1 &= {}_6C^{14}+{}_1H^1,\\
&= {}_6C^{13}+{}_1H^2,\\
&= {}_6C^{12}+{}_1H^3;\\
{}_8O^{16}+{}_0n^1 &= {}_7N^{16}+{}_1H^1,\\
&= {}_7N^{15}+{}_1H^2,\\
&= {}_7N^{14}+{}_1H^3.
\end{aligned}
$$

The second and third possibility in each case have the abundance of the new nucleus in their favor. The first possibility involves the creation of ${}_6C^{14}$ or ${}_7N^{16}$ neither of which corresponds to a known isotope of these elements. However, Fermi[2] has been led to postulate reactions of this type (emission of a proton) to explain the chemical processes necessary to entrain the β-ray activity induced in many elements by neutrons, so that it seems likely that ${}_6C^{14}$ or ${}_7N^{16}$ may emit an α-particle and return to the element originally struck by the neutron. Whether or not N or O is made radioactive by neutrons has not been conclusively established. If they are we shall have exchanged a neutron for a proton and an electron with presumably no permanent alteration in the nucleus originally struck by the neutron.

It is a pleasure to acknowledge the generous assistance given to me by Professor E. O. Lawrence in placing laboratory facilities at my disposal, in discussions and in practical aid in these experiments.

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May 31, 1934.

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[2] E. Fermi, La Ricerca Scientifica, Anno V, Vol. I, March, April, 1934.

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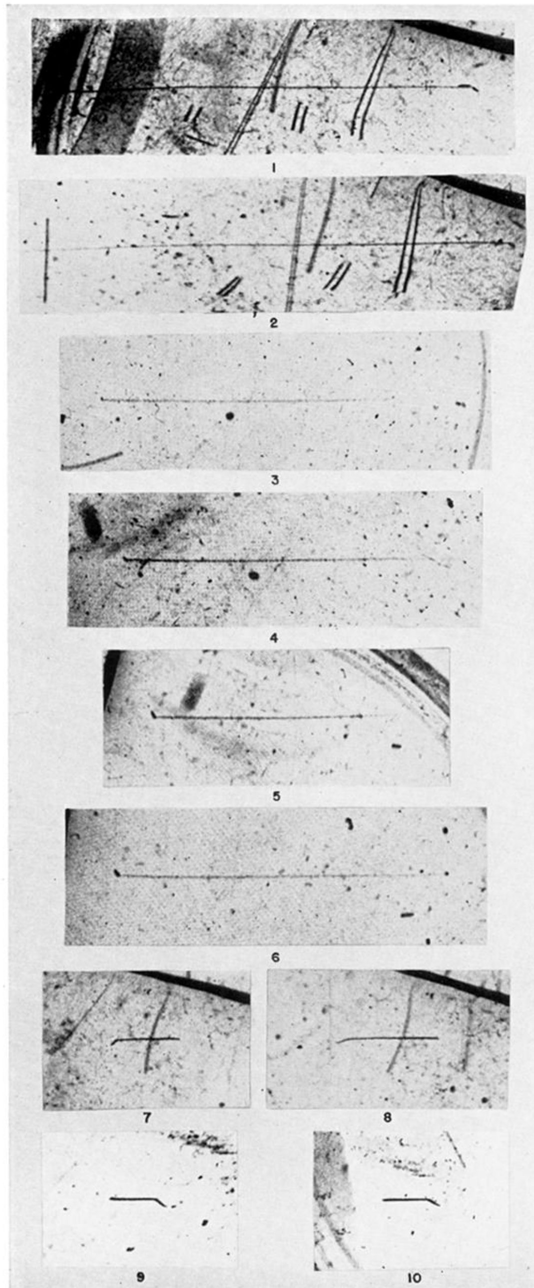

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