Interaction with the Absorber as the Mechanism of Radiation †*

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"We must, therefore, be prepared to find that further advance into this region will require a still more extensive renunciation of features which we are accustomed to demand of the space time mode of description."—Niels Bohr[1]

PAST FAILURE OF ACTION AT A DISTANCE TO ACCOUNT FOR THE MECHANISM OF RADIATION

IT was the 19th of March in 1845 when Gauss described the conception of an action at a distance propagated with a finite velocity, the natural generalization to electrodynamics of the view of force so fruitfully applied by Newton and his followers. In the century between then and now what obstacle has discouraged the general use of this conception in the study of nature?

The difficulty has not been that of giving to the idea of propagated action at a distance a suitable embodiment of electromagnetic equations. This problem, to be true, remained unsolved to Gauss and his successors for three quarters of the century. But the formulation then developed by Schwarzschild and Fokker, described and amplified in another article,[2] demonstrated that the conception of Gauss is at the same time mathematically self consistent, in agreement with experience on static and current electricity, and in complete harmony with Maxwell's equations.

To find the real obstacle to acceptance of the tool of Newton and Gauss for the analysis of forces, we have to go beyond the bounds of steady-state electromagnetism to the phenomena of emission and propagation of energy. No branch of science has done more than radiation physics to favor the evolution of present concepts of field or more to pose difficulties for the idea of action at a distance. The difficulties have been twofold—to obtain a satisfactory account of the field generated by an accelerated charge at a

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† *Introductory Note.*—In commemoration of the sixtieth birthday of Niels Bohr it had been hoped to present a critique of classical field theory which has been in preparation since before the war by the writer and his former student, R. P. Feynman. The accompanying joint article, representing the third part of the survey, is however the only section now finished. The war has postponed completion of the other parts. As reference to them is made in the present section, it may be useful to outline the plan of the survey.

The motive of the analysis is to clear the present quantum theory of interacting particles of those of its difficulties which have a purely classical origin. The method of approach is to define as closely as one can within the bounds of classical theory the proper use of the field concept in the description of nature. Division I is intended first to recall the possibility of idealizing to the case of arbitrarily small quantum effects, a possibility which is offered by the freedom of choice in the present quantum theory for the dimensionless ratio (quantum of angular momentum)(velocity of light)/(electronic charge)^2; then however to recognize the possible limitations placed on this analysis by the relatively large value, 137, of the ratio in question in nature; and finally to present a general summary of the conclusions drawn from the more technical parts of the survey. The plan of the second article is a derivation and resumé of the theory of action at a distance of Schwarzschild and Fokker, to prepare this theory as a tool to analyze the field concept. From the correlation of the two points of view, one comes to Frenkel's solution of the problem of self-energy in the classical field theory and

to new expressions for the energy of electromagnetic interaction in the theory of action at a distance. The third division, which is published herewith, is an analysis of the mechanism of radiation believed to complete the last tie between action at a distance and field theory and to remove the obstacle which has so far prevented the use of both points of view as complementary tools in the description of nature. It is the plan of a subsequent division to discuss the problems which arise when the fields are regarded as subordinate entities with no degrees of freedom of their own. An infinite number of degrees of freedom are found to be attributed to the particles themselves by the theory of propagated action at a distance. However, it appears that the additional modes of motion are divergent and have on this account to be excluded by a general principle of selection. Acceptance of this principle leads to the conclusion that the union of action at a distance and field theory constitutes the natural and self-consistent generalization of Newtonian mechanics to the four-dimensional space of Lorentz and Einstein.—J. A. W.

[1] Niels Bohr, *Atomic Theory and the Description of Nature* (Cambridge University Press, Teddington, England, 1934).
[2] Unpublished, see Introductory Note.

remote point and to understand the source of the force experienced by the charge itself as a result of its motion:

(a) An accelerated charge generates a field given, according to the formulation of Schwarzschild and Fokker, by half the usual retarded solution of Maxwell's equations, plus half the advanced solution. From the presence of the advanced field in the expression for the electric vector, it follows that a distant test body will experience a premonitory force well before the source itself has commenced to move. To avoid a conclusion so opposed to experience Ritz[3] and Tetrode[4] proposed to abandon the symmetry in time of the elementary law of force. However, it was then necessary to give up the possibility to derive the equations of motion and all the electromagnetic forces consistently from a single unified principle of least action like that of Fokker. More important, the sacrifice made to alleviate one difficulty of the theory of action at a distance did not help to solve the other, the problem of the origin of the force of radiative reaction.

(b) Experience indicates that an accelerated charge suffers a force of damping which is simultaneous with the moment of acceleration. However, the theory of action at a distance predicts that an accelerated charge in otherwise charge-free space will experience no electric force. To exclude the acceleration and thus to avoid the issue does not appear reasonable. Uncharged particles can be present and can accelerate the charge via gravitational forces. It seems just as difficult to explain the reactive force when other charged particles are present. They will indeed be set into motion and will act back on the source. However, if these elementary interactions have the purely retarded character assumed by Ritz, and also by Frenkel,[5] the reaction will arrive at the accelerated particle too late and will have the wrong magnitude[6] to produce the damping phenomenon. On the other hand, interactions symmetrical between past and future—the half-retarded, half-advanced fields of the unified theory of action at a distance—have so far appeared to be equally incapable of accounting for the observed force of radiative reaction, with its definitely irreversible character.

It is clear why the viewpoint of Newton and Gauss has not been generally applied in recent times; it has so far failed to give a satisfactory account of the mechanism of radiation.

The failure of action at a distance cannot pass unnoticed by field theory. The two points of view, according to the thesis of the present critique, are not independent, but mutually complementary. Consequently field theory, too, faces in the radiation problem a significant issue:

does this theory give an explanation for the observed force of radiative reaction which can be translated into the particle mechanics of Schwarzschild and Fokker, or does it likewise fail to provide a complete picture of the mechanism of radiation?

In attacking the radiation problem our first move, following the above reasoning, is to review the status of the reaction force in existing classical field theory. No more intelligible clue is found to the physical origin of the force in this theory than in the theory of action at a distance. Stopped on this approach, we take up a suggestion made long ago by Tetrode that the act of radiation should have some connection with the presence of an absorber. We develop this idea into the thesis that the force of radiative reaction arises from the action on the source owing to the half-advanced fields of the particles of the absorber; or, more briefly, that radiation is a matter as much of statistical mechanics as of pure electrodynamics. We find that this thesis leads to a quantitative solution of the radiation problem. Finally we examine some of the implications of this thesis for the conception of causality.

THE STATUS OF RADIATIVE REACTION IN FIELD THEORY

A charged particle on being accelerated sends out electromagnetic energy and itself loses energy. This loss is interpreted as caused by a force acting on the particle given in magnitude and direction by the expression

$$\frac{2 \text{ (charge)}^2 \text{ (time rate of change of acceleration)}}{3 \text{ (velocity of light)}^3}$$

when the particle is moving slowly, and by a more complicated expression when its speed is appreciable relative to the velocity of light. The existence of this force of radiative reaction is well attested: (a) by the electrical potential required to drive a wireless antenna; (b) by the loss of energy experienced by a charged particle which has been deflected, and therefore accelerated, in its passage near an atomic nucleus; and (c) by the cooling suffered by a glowing body.

The origin of the force of radiative reaction has not been nearly so clear as its existence.

[3] W. Ritz, Ann. d. Chem. et d. Physique 13, 145 (1908).
[4] H. Tetrode, Zeits. f. Physik 10, 317 (1922).
[5] J. Frenkel, Zeits. f. Physik 32, 518 (1925).
[6] J. L. Synge, Proc. Roy. Soc. London A177, 118 (1940).