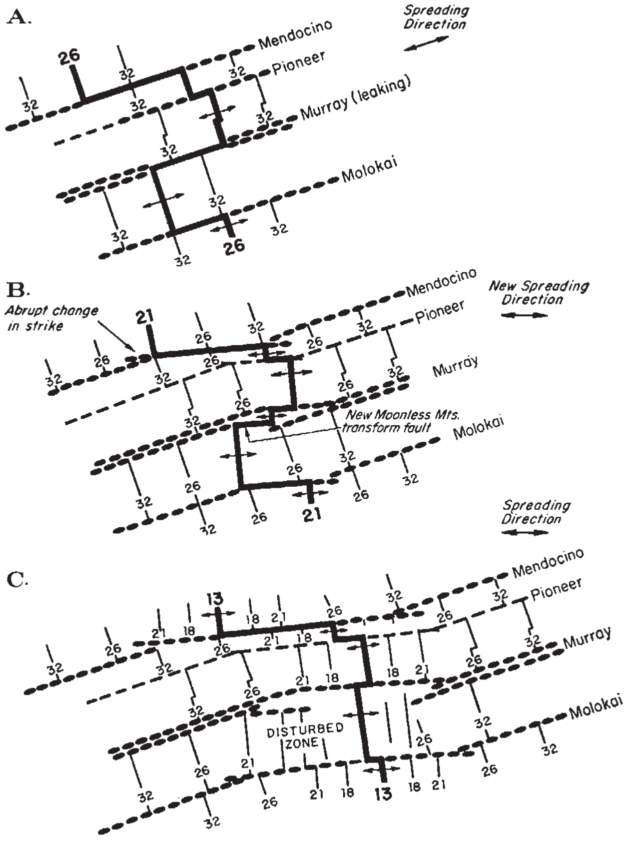

Fig. 6. Diagram of proposed history of plate motions and seafloor spreading in the north-eastern Pacific as deduced from the present day configuration of magnetic anomalies and fracture zones. The heavy line is the boundary between the plates. *A*, Configuration of spreading mid-ocean ridge at anomaly 26 time, Murray transform fault is leaking, creating great ridges and troughs. *B*, Configuration at anomaly 21 time, showing the effects of a change in spreading direction: Pioneer–Mendocino ridge segment is shortened, Pioneer, Mendocino and Molokai transform faults are reorientated and lengthened, Murray transform fault is shortened and widened, forming a new ridge segment and transform fault. *C*, Anomaly 13 time, the Murray–Molokai ridge segment has jumped east leaving the disturbed zone behind as a broken-off remnant of the east flank of the ridge.

occur because the overlapping crests could not spread at the same rate as the other crests in the region. This readjustment may cause only minor deformation and breakage near the transform fault. For example, along the Mendocino fracture zone, a change in spreading direction at the time of anomalies Nos. 23–21 apparently broke off the overlapping ends of the ridges and fractured the area of the old fault, creating a transform fault in the new direction (Fig. 5, refs. 9 and 12). If the configuration of a change is such that a fracture zone is overlapped as well as the ends of ridges, the zone may become inactive and terminate. This circumstance can account for the apparent branching or overlap and termination of some fracture zones in the central Pacific[13].

It seems that an entire section of ridge may become inactive if it is too far away from the general line of a ridge crest and a change in plate motion occurs. This explains the origin of the disturbed zone in the north-eastern Pacific (Fig. 6). Before the time of anomaly No. 21, the ridge section between the Murray and Molokai fracture zones was out of line so that the eastern crustal block formed a projection into the western one. At about anomaly No. 21 time this projection appears to have broken off, a new spreading centre opening farther to the east. Thus a section of the eastern block was left behind.

With conceptually minor modifications the hypothesis of seafloor spreading[14] can thus account for many characteristics of fracture zones, including creation and termination of zones; variations in length and spacing; regional differences in depth; great straight scarps and variations in scarp height; occurrence and orientation of rifted zones containing great linear ridges and troughs; and existence and location of abrupt changes in direction along the strike.

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Cosmology and Quantum Electrodynamics

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Further investigations in quantum elctrodynamics show how the radiative processes can be described without infinities in terms of cosmology and the direct particle theory of electrodynamics.

In an earlier article[1] we discussed a possible connexion between the quantum electrodynamics of phenomena in the local laboratory and the large scale structure of the universe. Such a connexion, on a classical level, was established a few years ago[2,3], following the pioneering work of Wheeler and Feynman[4,5]. It was shown, for example, that the choice of retarded potentials is not an arbitrary one, but is dictated by the expansion of the universe. Not all models of the expanding universe are able to achieve this result, however. For example, a unique choice of retarded potentials results in a steady state universe but not in the Friedmann universes[2,3,6]. This work was extended to non-relativistic quantum theory (see ref. 7 for details) and was briefly reported in ref. 1. There we considered how the spontaneous transitions of atomic electrons could be accounted for in the theory of direct interparticle action. In this theory the transitions occur not because of any special qualities assigned to the vacuum—as in the usual field theory—but because of the response of the universe. This response is the analogue of the one which gives rise to the radiative reaction on accelerating changes in classical theory.

The restriction to non-relativistic quantum theory in ref. 1 did not arise from any limitation of the direct particle electrodynamics. Indeed, as far as electrodynamics is concerned, one can easily write it in a relativistic form. The restriction arose from quantum theory. The method described in ref. 1 involved the path integral approach to quantum theory originated by Feynman[8]. This approach is eminently suitable for understanding the transition from classical to quantum physics, but is not so successful when discussing relativistic motions of spinning atomic particles. At the time of writing ref. 1 we had only the methods then available to draw upon.

Subsequently we have been able to extend the work to cover relativistic quantum electrodynamics and the so-called radiative corrections. It is this work which is reported in general terms here.

In the non-relativistic path integral approach the amplitude for a particle a to go from point 1 to point 2 in space time along a path $a(t)$ is given by

$$(\text{constant}) \,.\, \exp\{\mathrm{i}\, S\, [a(t)]/\hbar\} \tag{1}$$

where S is the classical action functional. The summation of (1) over all paths from 1 to 2 then gives the propagator $K(2,1)$. Although it does not seem possible to generalize this concept to spinning relativistic particles, an extension can be found which is sufficient for our purpose. This extension takes account of the following points: (i) instead of defining amplitude along a world line it seems more natural to define amplitude along an infinitesimal world tube surrounding a given path, (ii) summation of amplitudes leads to propagators as in the non-relativistic theory. If we consider particles (electrons, say) we first arrive at the propagator

$$K_0(2,1) = \frac{1}{2\pi}\left(\nabla_2 - \frac{im}{\hbar}\right) \left[\delta(q_{21}^2) - \frac{m\theta(q_{21}^2)}{2\hbar q_{21}}\, J_1\left(\frac{mq_{21}}{\hbar}\right)\right]\theta(t_2 - t_1) \tag{2}$$

where q_{21}^2 is the square of the interval between points 1 and 2, and ∇_2 is taken with respect to the coordinates of 2. This propagator restricts the motion to the inside of the future light cone. A similar propagator restricted to the inside of the past light cone can be obtained for positrons. And if we follow the particle–antiparticle interpretation of Feynman[9], we can relate (2) together with the corresponding form for positrons to the Feynman propagator

$$K_+(2,1) = \frac{1}{4\pi}\left(\nabla_2 - \frac{im}{\hbar}\right)\left[\delta(q_{21}^2) - \frac{m}{2\hbar q_{21}} H_1^{(2)}\left(\frac{mq_{21}}{\hbar}\right)\right] \tag{3}$$

It turns out that (2) is simpler to understand in terms of path integrals, while (3) is more convenient to work with in actual problems. (iii) The electromagnetic contribution to the amplitude can still be described by the simple form (1). This makes it easy to go from the non-relativistic theory of ref. 1 to the present relativistic theory.

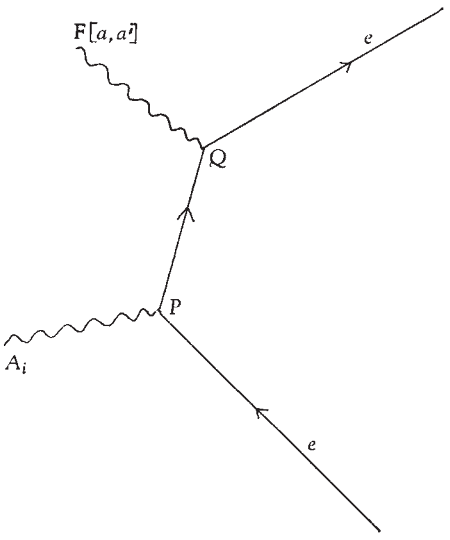

Fig. 1. Compton scattering. The electron is scattered by the external potential A_i as well as by the response F[a, a'] of the universe.

"Finite" radiative processes can then be worked out by calculating first the influence functional from the universe. This is the relativistic analogue of F[$a(\tau)$, $a'(\tau')$] described in ref. 1. We illustrate the general situation with a specific example, that of Compton scattering. In Fig. 1, the electron e is acted on by an external direct particle field A_i at P. This accelerates the electron, leading to the response of the universe F[a, a'], which acts at Q. Thus the electron is scattered twice. The order of the prescribed disturbance and the response can be interchanged, giving another diagram similar to Fig. 1. The result of the calculation is, of course, the same as that obtained by more conventional methods.

The influence functional F[a, a'] can be obtained in two ways. Either we can follow the method described in ref. 1 and take into account the details of transitions in the future absorber; or we can follow a procedure similar to the classical Wheeler–Feynman condition of complete absorption

$$\sum_{\text{all } a} \tfrac{1}{2}\,[\mathrm{F}^{(a)}_{\text{ret}} + \mathrm{F}^{(a)}_{\text{adv}}] \rightarrow 0 \text{ at infinity} \tag{4}$$

Here $\frac{1}{2}\,[\mathrm{F}^{(a)}_{\text{ret}} + \mathrm{F}^{(a)}_{\text{adv}}]$ is the time-symmetric direct-particle field of a typical particle a. The analogue of (4) relates to potentials and paths, but is too complicated to quote here. It is sufficient to state that it leads to the influence functional obtained by the first method.

We now turn to what may be the most crucial difference between the present point of view and the conventional point of view. In the latter a great deal of emphasis is placed on amplitude calculations. It is not amplitudes but probabilities that are experimentally measured, however. (The amplitudes are in general complex, whereas the probabilities are real.) In the present theory the response of the universe appears only through probability calculations. This makes a difference when considering radiative corrections.

In the usual method of calculating the self-energy of the free electron, for example, one looks for a change of the wave-function in question

$$\exp[-\mathrm{i}Et/\hbar] \rightarrow \exp[-\mathrm{i}(E + \Delta E)t/\hbar]. \tag{5}$$

The usual calculation leads to $\Delta E \rightarrow \infty$, and renormalization must be used to obtain a finite value. In the present theory, however, such a divergence has no meaning because we are concerned only with probabilities.

In certain cases dealing with external potentials (for example, the Lamb shift and the anomalous magnetic moment of the electron) a similar situation arises but with non-trivial results. Here the influence functional from the universe can be written as a sum of two contributions. The first, which produces infinities in the conventional calculations, disappears when probabilities are taken in the manner described. The second contribution gives finite results and survives when probabilities are taken. These finite results agree with those obtained from the usual theories after renormalization.

The theory has been extended to deal with closed loops in the vacuum, and the usual results for vacuum polarization have been obtained. We have not so far managed to obtain the required finite effect of vacuum polarization, however, except through the usual procedure due to Bethe and Pauli, a procedure we find difficult to interpret. Although an infinity again arises in an amplitude calculation it again disappears when probabilities are taken.

Finally, we emphasize that the present theory, besides making hitherto divergent processes convergent, yields all the usual practical results of radiation theory without ascribing independent degrees of freedom to the electromagnetic field. There are no quanta in the sense of the usual field theory. The present theory also makes it probable that the steady state model of the universe is the correct form of cosmology. We feel that the quantitative successes of the theory, reported here and in ref. 1, form a sounder basis for a cosmological judgment than the ambiguous astronomical data available at the present time.

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DNA Strand Breakage in Cells irradiated with X-rays

by

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The presence of oxygen during the exposure of mammalian and bacterial cells to X-rays does not affect the efficiency of single strand breakage of DNA, but in bacteria it interferes with strand rejoining processes which occur during irradiation.

ONE of the primary effects of the exposure of cells to ionizing radiation is the introduction of breaks into the main polynucleotide chains of the DNA molecule (compare ref. 1). Early studies on radiation induced DNA strand breakage demonstrated consistently that the number of double breaks produced (that is, interruptions leading to complete scission of the twin helix) is not increased by irradiation of the cells in oxygen. Precise evaluation of the number of breaks introduced into the DNA was difficult, for the procedures used for isolation of the DNA led to shearing damage. The results are, however, in agreement with the data obtained using isolated DNA[2] and bacteriophage[3] where the radiation damage was predominantly by direct action. Although an oxygen effect on strand breakage has been reported with isolated dry DNA[4], Hagen[5] has recently pointed out that the experimental procedures used in the earlier work were unsatisfactory. When pure DNA is irradiated in dilute aqueous solution, however, the effect of oxygen is complex (compare ref. 6) and the data are conflicting, but in any case such conditions may not constitute a realistic model for irradiation of DNA within a cell.

The problems involved in the isolation of DNA from cells have been largely overcome with the development by McGrath and Williams[7] of a method for isolating large single stranded molecules of DNA on alkaline sucrose density gradients. With this technique the number of breaks produced in the DNA of X-irradiated cells can be determined more reliably. In studies on the production and repair of single strand breaks in the DNAs of L5178Y murine lymphoma cells and *Micrococcus radiodurans* exposed to X-rays, an effect of oxygen on the efficiency of strand breakage was reported from this laboratory[8], but the present communication shows that these data have to be interpreted differently.

In the earlier experiments it was found that when cells were irradiated in oxygen one single break was produced in the DNA for approximately every 50 eV deposited in *M. radiodurans* and for every 70 eV with the murine lymphoma cells. This value for the efficiency of DNA strand breakage in *M. radiodurans* is the same as the recently corrected value for "fully protected" bacteriophage systems[3,9]. Unlike the bacteriophage studies, however, where the number of strand breaks was not influenced by irradiation in the presence or absence of oxygen, with the cell systems the number of single breaks found in the DNA was some three-fold lower when the cells were irradiated in anoxia at 0° C.

The measurement of radiation-produced strand breaks in the DNA of cells is complicated by the presence of enzymatic rejoining processes which restitute the breaks intracellularly[7,8,10] and by problems inherent in the analysis of molecular weight distribution from sedimentation profiles. Studies, which will be reported in detail elsewhere (unpublished work of R. W. S. and C. J. D.), have shown that in *M. radiodurans* the rejoining of broken DNA strands is particularly efficient after irradiation, and this repair process is inhibited by 0·02 M EDTA. We now find that when *M. radiodurans* is irradiated in buffer containing 0·02 M EDTA no significant difference is observed in the number of strand breaks introduced into the DNA when the cells are irradiated in either the presence or the absence of oxygen. In addition, a new method has been developed for the analysis of DNA sedimentation profiles which gives a more precise and reliable method for determining number average molecular weights. The application of this analysis to sedimentation profiles of DNA from *M. radiodurans* has shown that the molecular size distributions are consistently random for all conditions of irradiation. With the L5178Y murine lymphoma cells, however, anoxic irradiation in the previously reported conditions[8] yields sedimentation profiles with an abnormal molecular weight distribution which led to an overestimate in the computed average molecular weight. Evidence will be presented which indicates that the previously observed oxygen effect in murine lymphoma cells was due to this anomaly in the DNA distribution.

Single Breaks in the DNA of *Micrococcus radiodurans*

Cells labelled in their DNA with ^{3}H (methyl-) thymidine were rendered susceptible to lysis in sodium dodecyl sulphate (SDS) by treatment with the R1 enzyme fraction from *Streptomyces albus G* in 0·04 M veronal buffer *p*H 8·6 (ref. 10). This treatment alone does not affect the viability or alter the radiosensitivity of *M. radiodurans*. Following treatment with the R1 enzyme the cell suspension was exposed at 0° C to 220 kVp X-rays at a dose rate of 10^4 rads per min. The irradiated cells were then lysed by placing them in 0·1 ml. of a solution containing 0·2 per cent SDS and 0·02 per cent sodium deoxycholate in 0·2 M citrate-phosphate buffer *p*H 5·6 previously layered on top of a 5–20 per cent alkaline sucrose gradient. When lysis was complete the samples were sedimented in a Beckman *L2*-ultracentrifuge at 20° C. When centrifugation was completed the contents of the tubes were collected as two drop fractions and the molecular weight of the sample of DNA was determined from the distance sedimented according to the relation given by McGrath and Williams[7].

Fig. 1 shows the dose response relationship expressed in terms of the reciprocal of the number average molecular weight ($1/M_n$ is directly proportional to the number of breaks produced) when *M. radiodurans* is irradiated in the presence of oxygen or nitrogen, with or without the addition of 0·02 M EDTA. It is clear that when the cells