

*Research  
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# Research and Progress

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# Mechanisms of the Propagation of Energy in Physics and Biology

By

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The attention of physicists and biologists has been attracted within the last few years to a phenomenon known as the propagation or transmission of energy, which consists in the fact that the effect of wave or corpuscular irradiation can be plainly observed at a point remote from the point of absorption. The distances that come into consideration are naturally not very great, being no more than some 10 to 1000 Å, but they are still sufficient to ensure the separation just mentioned of the point of absorption of energy from the point of its manifestation. The conception of Propagation of Energy (*Energieausbreitung* or *Energiewanderung*) was introduced to bridge over the distance in space and without closer examination of the possibilities involved. The evidence which goes to support these facts comes chiefly from three different sources.

The first to be mentioned would be the investigations on the crystalline luminescent substances and here in turn chiefly those composed of zinc sulphide which N. Riehl bombarded with alpha rays, whereby a very high light yield (of the order of about 60 to 80 per cent) was observed. The alpha particles impinging upon a zinc sulphide crystal penetrate it, owing to their high velocity, in quite well defined and relatively thin channels, while the luminescence mechanism is connected with certain discrete additions of foreign matter (known as activators), which are present only in low concentration. Thus it was easy to calculate that a mean distance of 100 lattice planes from the aperture of entry of the alpha particle to the activators had to be bridged over, in order to ensure such an efficient conversion of the energy of the alpha particle into luminescent radiation.

Physics owes the elucidation of the second group of phenomena to experimental genetics, that is to say, to the application of the "hit principle" to the data obtained on experimental production of mutations by irradiation. It was found possible to determine that here also a migration of energy from the point of the hit to the point of the biophysical primary event must of necessity be assumed. The supply of energy takes

place here through the action of an electron, neutron, or X-ray quant. The results hitherto obtained have been interpreted as meaning that a mutation is generated by the energy of a single ionization which takes place within a certain definite volume, known as the target volume. On the other hand, when inducing gene mutations, we have to do with quite specific modifications of certain definite points within the individual gene, compared with which the target volumes must certainly be described as large. In this case it is possible to indicate a minimum size of the target volume: assuming a 100 per cent ion yield and knowing the approximate atomic density of the irradiated material and the reaction rate per unit dose, we arrive at a diameter of the "formal target volumes" for various gene mutations of the order of from  $1 \times 10^{-7}$  to  $3.5 \times 10^{-7}$  and even of between  $1 \times 10^{-6}$  and  $2 \times 10^{-6}$  cm for the inactivations of bacteriophages and viruses. Energy must therefore pass through from ten to one hundred carbon linkages on its passage from the point of its absorption to the site of its activity.

It is frequently assumed that phenomena of energy propagation also play a part in the assimilation of carbonic acid by green plants. But since the conditions here have not been elucidated so clearly as in radiation genetics, we refrain from going into these problems here.

The third group of experiments refers to the investigations carried out by G. Scheibe and his co-workers on the polymers of certain colours, in particular on the pseudo-isocyanines. The appearance of a sharply-defined resonance line foreign to the individual colour molecule and peculiar only to the polymer is first to be observed. Absorption in that line leads to excitation of the giant molecule which contains up to  $10^6$  single molecules of the dyestuff arranged in approximately nummular form, and it can be directly shown by experiment that energy is re-emitted or otherwise transformed from a point of that coin-shaped roll which is not the point of absorption. It has been found that the optical properties of these polymers are of such a nature that the absorption of irradiation only takes place when its electrical vector oscillates in the longitudinal axis of the polymer molecule. Now these substances can be purely mechanically aligned by utilizing their pronounced viscosity anisotropism and that effect demonstrated. On the other hand, a perfectly depolarized re-emission takes place in the absence of the alignment and polarized irradiation. That can only be understood by assuming that the polymers in their unarranged condition are somehow or other disarranged and bent or wrapped up, whereby a selection is made upon

absorption among the suitably oriented ends of the molecules. In re-emission, on the contrary, the ends of the molecules that do not agree with the direction of incidence of the electrical vector also participate. A second experiment confirms the propagation of energy in these molecules. The authors mentioned above have also been able to show that very low concentrations of certain substances (about  $10^{-6}$ ) have the tendency of withdrawing the whole of the energy absorbed from the molecules of the dyestuff polymers. It is thereby certain, for chemical reasons, that the attachment of a single one of these foreign molecules to a chain of  $10^6$  of the colour molecules is able to extinguish the fluorescence. That is naturally only possible when the exciting energy is free to change its position within the chain.

We recently published a comprehensive discussion in which we systematically analysed the possibilities of phenomena of that nature relating to the propagation of energy, basing our remarks on general physical facts. We refer to a few clearly distinguishable phenomena, the occurrence of which chiefly depends upon the nature of the distance between the components of the material and therewith of the binding forces.

*The electronic form of the propagation of energy.* It is well known that matter in the condensed phase possesses a spectrum of electronic energy which, unlike the atomic spectrum composed of single lines, consists of groups of lines assembled to form "bands". Non-conduction solid crystals, in particular, possess that property. A solid body of that nature may be regarded as being in many respects a giant molecule containing as many electrons as do the atoms of which it is composed. These electrons distribute themselves on the terms of the electron spectrum, whereby differences in the nature of the occupation of the terms may appear which make it possible to understand the fundamental difference between electrical conductors and isolators. It is a peculiarity of condensed matter that the individual electrons can no longer be ascribed to the individual atoms, but belong to the crystal in general. Energy of excitation imparted to one of these electrons is imparted, so to say, to the whole crystal. If the energy is supplied locally, as in the case of X-ray or corpuscular radiation, there appears a condition of excitation of the electrons as the result of absorption, which is to be found throughout the whole crystal, when it happens to be an ideal crystal and the temperature is sufficiently low. The investigation of zinc sulphide luminous substances has shown that ranges extending to  $10^{-5}$  cm still take part in the energy

of excitation at room temperature. That universal presence of the excited electrons is generally connected with an electrical conductivity of the substances when energy is supplied (the internal photo-electrical effect of crystals).

*Transmission of energy through dipole resonance forces.* The conditions that occasion the electronic form of the propagation of energy are that the spaces between the atoms must be so small that an appreciable transgression of the charge clouds of the electrons of the individual atoms takes place. By increasing the distances, that possibility of the propagation of energy breaks down. Even in such an event, however, as we have been able to demonstrate, a propagation of energy can be realized. Let us assume that the matter consists of atoms of the same nature or contains a large number of atoms of the same nature; these atoms then possess at all events corresponding differences of energy in the term system. Upon exciting an atom it may be expected that other atoms tuned to the same wave length will oscillate with it, as is well known in exactly the same form from wireless technics. A form of the propagation of energy appears here which is not connected with the common possession of an electron and its energy of excitation, but is based upon the fact that the alternate action of the individual oscillators tuned to the same wave length causes energy to shift perpetually from one of the atomic transmitters to the other, so that it can thereby bridge over a fairly large range of space.

*Other possibilities for the propagation of energy.* We have just mentioned the two most important possibilities for the propagation of energy and intend to deal only summarily with the others, which are only of supplementary importance. There are first of all those cases in which the propagation of energy is only made possible by intervention of the internal energy of the molecules or molecular complexes, such as is always present in the form of oscillations of the atoms against one another. The appearance of that form of energy can compensate the energetic difference between terms or bands and thereby make the propagation of energy possible. One might in such a case speak of a propagation of energy by cooperation of numerous degrees of freedom. Further, a transmission of energy over considerable distances is naturally occasionally to be taken into consideration by the direct transportation of excited or ionized particles, although probably not too great an importance can be attached to that form of the transmission of energy owing to the short duration of existence of the excited or ionized conditions in liquids,

and to the fact that the speed of diffusion in the solid state is generally too low.

Finally, N. Riehl and K. G. Zimmer have recently designated the wandering of points of interference, postulated by J. A. Hedvall on the basis of his experience with chemical reactions, as being a form of propagation of energy which had hitherto remained unobserved. It appears, however, as if that is to be ascribed—in certain instances at least—to a special case of the electronic form.

If it be asked on the basis of these remarks as to what possibilities are realized in certain definite cases, one arrives at much the following result: There can be no doubt that it is the electronic form in the case of the crystalline luminous substances, in which physics is particularly interested; in the case of Scheibe's polymers, it is very likely the form produced by dipole resonance forces. But the question as to what form must be assumed for the propagation of energy in biological material cannot be answered quite so unambiguously. For experimental conditions so unequivocally definite that the appearance of one of these mechanisms in the pure form might be expected, are only present in the two phenomena mentioned that have been investigated by physicists. The actual conditions in experiments in radiation-biology are different and neither the material nor the other conditions can be regarded as being homogeneous and constant; it may rather be expected that conditions will vary from case to case. Under this heading we intend to deal only with two problems: These are the possible connection between the structure of the reacting unit and the form of the mechanism of the propagation of energy; and, secondly, the influence exerted by modification of the target volume on the reaction rate induced by irradiation.

*Dependency on the structure of the reacting unit.* By way of example we shall consider the mutations and inactivations of genes, viruses, and bacteriophages. To begin with, we do not know much about the structure of these units, but it is known with certainty that we have to do with nucleoproteids. The structure of these nucleoproteids can be imagined in a quite general way, chiefly on the basis of the latest investigations conducted on the virus of the tobacco mosaic disease (by G. Schramm in 1941), as representing a longish protein body with side chains of nucleic acid disposed on its surface; it is also probable that the planes of these nucleic acids run parallel to one another. It is then a very plausible assumption that these nucleic acids permit of a mutual propagation of energy by the action of dipole resonance similar to those occurring

in Scheibe's polymers. Such an assumption appears plausible particularly for ultraviolet light, because it is known that the effective spectrum for inducing mutations by ultraviolet irradiation approximately agrees with the absorption of nucleic acid. It would be very interesting for that reason to gain more accurate knowledge of the target volumes for mutations induced by ultraviolet rays and for the inactivation of bacteriophages and viruses, and to compare them with our previous knowledge of the quantities and probable arrangements of the nucleic acids. On the other hand, it is perfectly possible and, indeed, probable that regions of the electrons with a band-like character occur in the protein body itself; an answer cannot at present be given to the question whether they extend over the whole length of the protein body. The propagation of energy in the protein body itself (in the electronic form) can also be excited by irradiation with high energy radiation; but this is unlikely in the case of ultraviolet excitation, since the absorption-bands of these substances lie within ranges of shorter wave length. In the case of high energy radiations, it is very probable that the greater part of the energy absorbed is imparted to primarily the protein body, because the number of atomic groups is very large there. Energy may also be transferred from here without irradiation to nucleic acids and be propagated there by dipole resonance forces as in the case of excitation by ultraviolet rays. In this connection it would again be most interesting to compare the target volumes for ultraviolet with those for high energy irradiation in order to form conclusions as to whether both forms of the propagation of energy or only one are actually present in structures of that type. Further the point can certainly not be lightly dismissed that the propagation of energy might also be able to make itself noticeable by means of diffusion in biological reactions induced by irradiation, say, in such a way that certain chemical reactions are induced in the surrounding liquid, whereby the products created diffuse to susceptible points of the reacting units, where they might induce corresponding modifications. Although we do not attach too much importance to that possibility, we mention it for the sake of completeness. Finally energy may be supplied from the surroundings by propagation with the cooperation of numerous degrees of freedom, should the medium containing the reacting unit have a corresponding structure.

Although our knowledge of the structure of the biological reacting units is still very imperfect, the example given shows clearly enough that we certainly cannot expect a single form of the propagation of



energy to apply in every case, but that a discussion of the special features of each single case will be indispensable. It is to be hoped that a detailed analysis of the target volumes using various forms of irradiation may make it possible to elucidate many problems relating to the structure of the reacting units and the distribution of sensitive regions. For it is at once evident that the forms of the mechanism for the propagation of energy are to a great extent dependent upon the structure of the units taking part in the reaction.

*Influence of external factors on the target volume.* It is well known that the proportion of the mutations induced by the same dose of the identical rays can be influenced to a certain extent by various external conditions, such as the age and the physiological condition of the cells or the nature of the tissue. A modification of the reaction rate after application of the same dose of irradiation might have one of two meanings: We might have to do either with a change of the yield of ions (or of the quant yield) of the reactions in question or with a change regarding the size of the target volume within which a propagation of energy takes place without sub-threshold dissipation. Both these possibilities are conceivable, but the second would appear to be the more probable.

Regarded formally, an increase of the reaction rate means an increase of the target volume and vice versa, because the size of the target volume, conditions being otherwise constant, is calculated from the reaction rate per unit dose. The size of the target volume in turn depends on the nature of the propagation of energy in the substance in question. It appears to be a very plausible assumption that the structure of a biological reaction-unit, in view of the complexity of its nature, might under given circumstances experience certain modifications. There are present in the cells, for instance, micella and fibrilla shaped proteins and nucleoproteids, and these may be in a more or less stretched state, according to the prevailing chemico-physiological conditions. Depending on the type of tissue, and on the physiological state and stage of the life cycle of the cells, the vital structural units of the cell may be more or less closely bound with various chemical constituents of their immediate surroundings: The nucleic acid content of the chromosomes, for instance, and the distribution of various proteins in the nucleus appear to undergo a cyclic change (T. Caspersson 1941). It appears to be not only conceivable, but quite probable that modifications of that nature may be able under certain circumstances to exert a fairly considerable influence on the propagation of energy, whereby the size of the target volume would

be changed correspondingly. It is thus conceivable that, because of the presence of various degrees of stretch and of different quantities of the absorbed nucleic acids in the chromosome, a definite form of the transmission of energy (propagation of energy by dipole resonance forces in the side chains of the nucleic acid) might be present or excluded, or even that the likelihood of the conversion into heat or the like might undergo substantial modification. The changes in the propagation of energy arising in that way, and the corresponding changes of the size of the target volume would lead to corresponding changes of the reaction rate per unit dose.

Also in this field, it is not yet possible to make definite statements, for the most part because of our defective knowledge of the structure of the reacting unit. In a general form, however, the remarks made above furnish a thoroughly plausible explanation of the actual conditions in various experiments on the application of radiation in biology. It is desirable to carry out an exact analysis of the target volumes in cells at various stages of physiological development by the application of various types of irradiation in inducing a definite reaction. Important information might also be gained from experiments on models of familiar material easier to analyse, such for example as Astbury's keratin fibrillae (1936) which are subject to reversible contraction under the influence of certain definite factors.

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We have attempted to bring certain experimental results obtained in the difficult boundary region between physics and biology closer to an explanation in terms of modern physical conceptions. In view of the present state of our knowledge on the subject, it is perfectly evident to us that such a project can only be regarded as a suggestion. Apropos of this, it must be stated that introducing the conception of the propagation of energy to biophysical theories opens up wide new vistas; for any attempt to represent biological phenomena by means of physical models leads to far greater difficulties than are to be met with even in the most complicated matters of purely physical character. These difficulties arise from the special nature of the material under discussion providing a confusing multitude of parameters, owing to which the phenomena at first receive the character of being hopelessly irreproducible. Under such conditions, conceptions such as that of the propagation of energy prove of value. For it is possible by their use effortlessly to maintain and to connect with one another such simple model conceptions

as are based on the theory of hits; and probably these conceptions may be developed also for the nature of the genes or for the reaction mechanism of the reacting unit, without allowing the unusually large variations caused by "external factors" to take away the possibility of setting up any theory at all. It is improbable that this state of affairs will undergo a change in the immediate future, and we shall have to content ourselves in our efforts to cast a little light on biophysical phenomena by setting up relatively rough model conceptions, which reproduce the behaviour of biological matter only in general outline. But it is at any rate a beginning.

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