*The structure of radiation.* By Dr Edmund C. Stoner, Emmanuel College.

[*Read* 19 January 1925.]

*Introduction.*

The difficulties in the way of attaining a coherent view which embraces both the structure of the radiation field, and of matter, and allows the appropriate interchanges of energy between them, are well known*. They are indeed such as to seem inherent in the phenomena themselves, and to suggest that only a formal treatment can be given. Interference, and "pure optical" effects generally are such as can be most simply explained by assuming transverse waves to spread out from the source of light. If atoms emit independently, it must be supposed that it is not merely statistical average effects which are observed, but that the light coming from each individual atom can spread spherically, and that interference can occur between resulting secondary wavelets. The effect produced at a point of observation is a function of its distance from the source not along one path only, but along all possible paths, and the maximum path difference for interference gives a measure of the "coherence length" of the train of waves, that is the number of waves emitted by the source without change of phase. To account for the whole range of phenomena typified by the photoelectric effect, on the other hand, some form of light quantum hypothesis which supposes radiation to be propagated by discrete entities, small "bundles of energy," seems absolutely necessary. Neither the wave nor the quantum hypothesis, in its present form, however, seems to offer any means of explaining the phenomena covered by the other; indeed each hypothesis seems definitely, in many cases, to rule out the possibility of the occurrence of effects which are actually observed.

An attempt to overcome some of the difficulties has been made by Jeans and Bohr, by the former in terms of what may be called "waves of probability," and by the latter in terms of "virtual fields of radiation." Neither of these view-points suggests any satisfying physical picture, and both involve the abandonment of the principles of conservation of energy and momentum applied to individual emission and absorption processes. This step at present seems too

* For a general account of the present status of the problem see Jeans, *Report on Radiation and the Quantum Theory* (2nd ed. 1924), particularly Ch. VIII, and Bohr, *On the Application of the Quantum Theory to Atomic Structure*, Pt I (1924), particularly Ch. III, supplemented by Bohr, Kramers and Slater, *Phil. Mag.* 47, 785 (1924).



https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

far-reaching unless definite evidence can be found in its favour, for it is precisely on the basis of those conceptions which lead to the conservation laws that the most striking triumphs of the quantum theory have been founded; and such evidence as there is seems antagonistic. It seems desirable, then, to suppose these laws to hold, and to explore the problem as far as possible, assuming their validity.

It will be shown here that, assuming energy and momentum to be conserved in the individual processes of emission, absorption and scattering, there seems no escape from the conclusion that radiation is propagated by linearly directed quanta. Evidence is brought forward which suggests that these quanta are spatially localised longitudinally as well as laterally, having, that is, a point rather than a line structure.

The properties of the radiation field will depend on the characteristics of the quanta (or "quants" as they may be termed when regarded as discrete physical entities) of which it is constituted; the specification of these involves a more detailed knowledge of the actual transition processes than is at present provided by theory. The evidence for discrete quants, however, seems sufficiently strong to justify a discussion of the question as to whether there is any possibility of associating with them properties which would enable them to produce effects such as are ordinarily explained on the basis of a wave structure of radiation. The conception of the phase of a quant is introduced and it is shown that if a quant has a constant phase at emission, and if further the effect of a quant on atoms which it passes may be supposed to persist, it seems not impossible to obtain a tentative explanation of interference phenomena.

Some of the characteristics of quants may be deduced from the polarisation phenomena observed, particularly under the influence of magnetic and electric fields. These are briefly considered in relation to the angular momentum changes which take place in the atoms on emission and absorption. It seems as if the ultimate key to the problem as to how quants can "imitate" waves is to be sought by investigating phenomena in which the emitting or absorbing systems are restricted as to orientation, and the polarisation of the light is of a definite type.

### *The Linear Direction of Quanta.*

In whatever form radiation exists in free space there can be no doubt that matter can only gain or lose radiant energy in complete quanta. If as a result of a quantum switch an atom loses an amount of energy $E$, this energy must then be present in free space in a form, and with properties which must be deduced from the be-

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

haviour of matter surrounding the emitting source. From this it is concluded that radiant energy travels with a velocity $c$, and that a quantum emitted may be re-absorbed as a whole. The question at issue is whether quanta emitted from atoms spread spherically, with power to collapse at one point, or travel linearly. The former idea will be considered first.

On the spherical spreading view, which is widely held—Jeans states that "it is now generally accepted that in regions where matter is absent radiation is propagated in accordance with the classical laws of Maxwell"*—the field surrounding an emitting atom may be considered as being such as would result on the classical theory from the vibrations of an electron in an appropriate orbit. In the hands of Bohr this view has not been unfruitful. In the quantum picture of the atomic change resulting in such emission, however, there seems no possibility of introducing an electron vibrating in the required way. The electron is an "effective" one. Moreover, insuperable difficulties arise when absorption is considered; any spreading, and consequently weakening, seems incompatible with the view of absorption which the quantum theory suggests as the simple inverse of emission, in accordance with the wider generalisations of thermodynamics.

Jeans attempts to evade some of the inconsistencies by a reinterpretation of the meaning to be assigned to the symbols $X$, $Y$, $Z$, expressing on the old electrodynamics the electric force components, and the amplitude $A$ of the waves. "We can avoid all contradiction with the conceptions of the quantum theory," he says, "if we suppose that $X$, $Y$, $Z$, or some functions of these quantities, measure, in some way at present unknown, the probabilities of jumps in the velocity and perhaps also in the position of an electron which forms part of an atomic system."† Further, $A^2/h\nu$ may be taken as a measure of the probability of a quantum $h\nu$ of energy being transferred in unit time.

It is here suggested that such a treatment virtually begs the whole question. Consider a single atom which has emitted a quantum of radiation which may be supposed to spread through space as a spherical wave train. At any particular point there is a probability depending on $A^2/h\nu$ of its being absorbed. When it is absorbed, the whole wave system disappears; and the idea of such disappearance seems no more comprehensible for probability waves than electromagnetic ones. "From the point of view of the old mechanics," Jeans says, "[photoelectric] transfer of energy is entirely unintelligible."‡ If the different parts of the wave system do not carry appropriate energy, however, there seems little value in postulating its existence—for our interest in waves depends fundamentally on their energy-carrying properties; if they do, it is

* *L.c.* p. 80. † *L.c.* p. 81. ‡ *L.c.* p. 82.



https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

necessary to suppose that absorption begins at a particular point on the wave front (or that energy is absorbed from a part of the wave train that has passed) and that the energy all "collapses" on to this point, if absorption is always by quanta; this is equivalent to postulating a particularised point of absorption, which at once undermines the attempted explanation of interference.

Jeans' treatment, then, while of value in bringing out difficulties, is purely formal. It may be briefly summarised by saying that if, to account for interference, it is desired to retain the idea of waves spreading spherically from an emitting atom, it is necessary to reinterpret $A^2/h\nu$ in terms of probability of energy transfer from the whole wave system.

The idea that emission of radiation is completely directed—the "light-dart" hypothesis—is associated with the name of Einstein, who derived arguments in its favour from a consideration of the recoil of atoms from radiation necessary to maintain the correct energy distribution under temperature equilibrium conditions*. The conclusion has not been generally accepted†, and is not a necessary consequence of Planck's law. Breit‡ has in fact shown that while linearly directed quanta are not inconsistent with the known equilibrium conditions, these can be maintained equally well by assuming that emission is non-directed, if account is taken of the fact that finite though small ranges of frequency are associated with quantum transitions.

Unless somewhat fantastic conceptions are adopted, however, a simple consideration of photoelectric absorption seems to provide a very cogent argument in favour of linearly directed quanta. In complete accord with electromagnetic theory, and relativity, experiments on the pressure of radiation have shown it to be statistically true that absorption of radiant energy $E$ is associated with transfer of momentum $E/c$. According to modern views all absorption of radiant energy takes place by quanta $h\nu$, and it seems difficult to escape the conclusion that this process is associated with transfer of momentum $h\nu/c$. Actually the association is only known experimentally to be true for a large number of switches; if in some switches less momentum is transferred, in others more must be. Now for waves with energy $E$ the total associated momentum varies from zero for spherical waves to a maximum of $E/c$ for plane waves. Unless some artificial means of increasing this maximum is devised, it seems, therefore, that all absorption corresponds to absorption of plane waves—in other words, since absorption takes place only by quanta, that quanta are linearly directed.

The importance of this conclusion may make it worth while to look at the question from a slightly different standpoint, which

* Einstein, *Phys. Zeit.* 18, 121 (1917). † Cf. Bohr, *l.c.* p. 40.
‡ Breit, *Phys. Rev.* 22, 313 (1923).

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

enables the distinction between the classical and quantum pictures of emission to be seen more clearly. Consider a classical radiator emitting spherical waves. The total momentum associated with the wave system is zero. If absorption occurs over a certain area, momentum is transferred, the momentum of the modified wave system now being no longer zero. The conception of spherical radiation can only be considered as consistent with the energy-momentum relations if absorption can occur over part of the wave front, that is, assuming that a single quantum is associated with the whole wave system, if absorption of fractions of quanta can take place. That quanta are linearly directed seems to follow uniquely from the fact that emission and absorption of radiation can only occur in complete quanta.

It is more difficult to find conclusive objections to the "virtual field" view than to that of Jeans, partly because of its greater vagueness; but it has a number of unsatisfying features. According to the conceptions put forward by Bohr, Kramers and Slater, there is some interconnection between two atoms one of which emits, and one absorbs, on account of the virtual field surrounding each, but although the probabilities of absorption and emission transitions depend on the character of the fields, the times at which corresponding transitions occur are not related in any definite manner. If one atom undergoes an emission transition, a second atom at a distance $l$ may undergo a corresponding absorption transition, but the second event does not necessarily occur at a time $l/c$ after the first. There seems no reason, in fact, why an absorption switch should not actually occur before the "corresponding" emission switch.

Now in Wilson's photographs* large numbers of definite pairs of long and short range tracks occur (those referred to as class 2), the smaller of which can scarcely be interpreted as due to anything other than an electron ejected from the second atom by the $K$ radiation emitted by the first on its return to a normal state after a fast $\beta$ particle, represented by the longer range track, has been ejected from it. The mere fact that such tracks are definitely associated in pairs strongly suggests that the second switch is definitely the result of the first switch rather than that it occurs by chance, or probability, on account of the virtual field surrounding the first atom.

On Bohr's view the pairing might be linked up with the changing of the virtual field resulting after a transition switch. Bohr, however, says that "the occurrence of a certain transition in a given atom will depend on the initial stationary state of this atom itself and on the states of the atoms with which it is in com-

* Wilson, *Proc. Roy. Soc.* 104, 1 (1923), see p. 18.

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

munication through the virtual radiation field, but not on the occurrence of transition processes in the latter atoms."* On the present view, the time between the switches should be $l/c$; but the possibility of experimental verification of this seems remote.

As to conservation, however, it may at least be said that it seems unwarranted to assume that it does not hold in individual processes when there is no definite evidence of its breakdown, unless the supposition leads to a much more complete and satisfying explanation of observed phenomena than has hitherto been put forward.

The argument developed above for directed quanta is quite independent of the evidence which is gradually accumulating in connection with mono-electric quantum scattering, particularly in relation to the "fish tracks," due to recoil electrons, observed by Wilson and Bothe.

Skobelzyn† also has recently used the cloud-chamber method to investigate the secondary radiations produced by $\gamma$-rays. The greater range of the recoil electrons in this case enables more precise measurements to be made, and the results are definitely in accord with a mono-electronic scattering of linearly directed quants, as opposed to spherically spreading radiation. Evidence from this direction will not, however, be further considered here, but reference may be made to recent papers on this question by Compton‡.

### *The Spatial Localisation of Quanta.*

Accepting tentatively the conclusion that quanta are linearly directed, and hence that they may be pictured crudely as having a small, though undefined, cross section, the question arises as to their degree of extension in the direction of propagation. To suit different circumstances values varying from zero to infinity have been postulated. Assuming quantum emission, however, the length may be taken as finite, and the difference of degree assumes importance as a difference in kind when an attempt is made to decide whether the length is of the order of one or a million wave lengths.

Stationary waves will first be considered. For the derivation of the correct Planck distribution law for equilibrium temperature radiation it is necessary, as is seen most clearly in Jeans' treatment, to regard the radiant energy as concentrated in integral multiples of quanta $h\nu$ in definite stationary ethereal vibrations set up in the impermeable isothermal enclosure. The energy of a whole quantum must be supposed to be capable of localisation within a volume $\lambda^3$. Since stationary waves may be regarded as due to the super-

* *Phil. Mag.*, *l.c.* p. 791.
† Skobelzyn, *Zeit. für Phys.* 28, 278 (1924).
‡ Compton, *Phys. Rev.* 23 (1924).

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

position of progressive waves, although in terms of "quants" the process may be obscure, it seems necessary to suppose that in progressive "waves" also, the energy is similarly concentrated.

This may be brought at once into relation with the characteristics of quantum transitions. Adopting a straightforward view, the length of a quantum could not be greater than $ct$, where $t$ is the time between the beginning and end of a transition. These transitions are usually regarded as "sudden" jumps, which is unfortunately somewhat vague. The conception may, however, be rendered more precise by the consideration that the time $t$ occupied by a transition must be indefinitely small compared with the duration of life $\tau$ of the atom in a stationary state, for otherwise there would not be that sharp distinction between stationary and intermediate states which forms so essential a feature of the quantum picture of the atom. Now the mean life of a number of atoms in upper stationary states has been estimated by a variety of methods* and the results are in agreement that the time $\tau$ is generally of the order $10^{-8}$ sec. In this time a wave train of some $10^6$ wave lengths could be emitted; so that in the time $t$ of a transition, the length of the train which could be emitted must be indefinitely less than this. The usual view of a transition, then, is in accordance with the supposition that the energy of a quantum is localised longitudinally within a length of the order of one wave length.

With a view to a possible explanation of interference, however, it is natural to attempt to retain waves even of the rope type, and to attribute to the train such a length as the observed "coherence" would demand. If an eel-like quantum (having a finite length, with head and tail) is assumed, difficulties of a type previously mentioned immediately arise. If the energy is distributed along the eel, so that the waves have some physical reality, since absorption, being by quanta, corresponds to the disappearance of the whole eel, either absorption of radiation which has passed a point can occur, or absorption necessarily begins at the head of the eel. Both alternatives are unsatisfactory, the former robbing the assumed structure of physical reality, and the latter undermining its power to explain interference effects.

An important experiment, beautifully simple in idea, recently described by G. P. Thomson†, sheds a good deal of light on the question, and supports the above views in that the results seem quite incapable of explanation on the basis of a line-like, as opposed to a point-like, structure of the quantum.

The light emitted by positive rays moving transversely to a slit was examined spectroscopically. The disposition of the slits was such that, for a single moving emitting atom, only the light emitted

* E.g. Tolman, *Phys. Rev.* 23, 693 (1924); Milne, *Phil. Mag.* 47, 209 (1924).
† Thomson, *Proc. Roy. Soc.* 104, 115 (1923).

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

during a very short determinate time could affect the spectroscope. In a typical experiment quoted, for $H\beta$, this corresponded to 3·5 cm. as the "length of the longest train of waves which could enter the spectroscope from one atom." Now Thomson calculates on the basis of the usual interference theory that 6 cm. is the least distance over which the vibrations of a radiator must extend without change of phase for the width of the line to be as small as it is. This then gives the minimum length of the quantum (on the eel view) corresponding to the classical wave train, and it would be anticipated that if only the energy in a fraction of this length could reach the point of observation, the normal effects of $H\beta$ frequency radiation would be modified. Yet in the experiment no modification in the spectral character of the light was observed.

From this it would seem to follow that the length of a quantum probably bears no relation to the coherence length of the classically corresponding train of waves; the characteristic properties of a quantum, which determine its effect on matter, being localised in a length certainly much less than this.

Thomson puts forward five possible deductions, not necessarily mutually exclusive, of which the most satisfactory (2) appears to be that the energy of the quanta is concentrated in points and not in lines. The others may be briefly criticised: (1) that one emitting particle emits several quanta consecutively in phase with each other, and (3) suggesting a "trigger effect" in absorption, are not in harmony with the quantum picture of the atom; (5) that "an electron can collect energy from a wider area than seems possible on the classical theory" is rendered improbable by the arguments advanced above; (4) that conservation of energy is statistical only, is, as Thomson remarks, difficult to distinguish from (2) experimentally, but, as already discussed in connection with virtual fields, the idea is so far-reaching and disturbing that much more evidence is required before it should be accepted. Deduction (2) may be tentatively accepted, with the obvious reservation that "point" is not to be taken in the strict mathematical sense.

It is certainly going beyond the experiment to suppose that the quanta are indefinitely small. Assuming quantum emission, what the experiment does definitely show is that there are phenomena of the "pure optical" type which it is impossible to explain by an attempted association with a quantum of a classical wave structure, but that these phenomena are consistent with a point-like quantum.

In this connection reference may be made to a series of papers by Ornstein and Burger* in which, by an extension of a method used earlier by de Broglie†, a kinetic theory treatment is applied to the determination of the equilibrium between radiation and

* Ornstein and Burger, *Zeit. f. Phys.* 20, 345, 351 and 21, 358 (1924).
† de Broglie, *Journ. de Phys.* VI, iii, 422 (1922).

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

electrons, the radiation being considered as concentrated in quants with effective cross sections varying as the square of the wave length. It is shown further that the quant may consistently be supposed to have its energy concentrated within an "effective sphere" of volume proportional to $\lambda^3$, the factor, somewhat crudely estimated, being of the order of a tenth.

Any attempt to estimate the "size" of a quant involves the difficulties as to the interpretation of the terms used (a similar difficulty arises in connection with the size of the electron), and there is necessarily considerable vagueness; bearing this in mind, however, there can be little doubt that the evidence so far reviewed, if interpreted in any straightforward manner, leads definitely to the conclusion that radiation is propagated by linearly directed, spatially localised quanta.

## *Interference.*

Although arguments in favour of regarding quanta as "accumulations of energy in certain minute spaces" that have hitherto been put forward have been somewhat indefinite, the simplicity of the view, and its power of co-ordinating so many phenomena, would have made it much more generally acceptable but for the obvious grave objections that can be brought against it.

The main objection is clearly stated by Lorentz*. If quanta are mutually independent, interference and resolving power effects show that each quantum must have considerable length, of the order of some million wave lengths, in the direction of propagation, and also a considerable breadth at right angles to it, of the order of the maximum useful diameter of a telescope objective.

Bohr† further maintains that the light-quant picture "excludes in principle the possibility of a rational definition of the conception of a frequency $\nu$."

While completely adequate answers to these objections certainly cannot at present be given, in view of the strength of the light-quant position, it seems legitimate to inquire what sort of modifications in outlook are necessary, or what additional properties of radiation must be postulated, in order that interference and allied phenomena might be explained on a light-quant basis.

As to Bohr's objection, it does not seem to carry great weight; for if a quant is assumed to have periodic properties, so that it varies periodically in some way as it travels through space, a conception of frequency and also of "wave length" can at once be arrived at. The "wave length" is, of course, a term that can only be used by analogy, in that adoption of the quant involves abandonment of the wave picture. The "wave length" may be defined as

* See Jeans, *l.c.* p. 79.

† Bohr, *l.c.* p. 35.

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

the least distance between two points at which the quant has the same characteristics; the period as the time between two returns to the same state, and the frequency the inverse of this. The idea of the "phase of a quant" may also be introduced, a measure of it being given by the time which has elapsed since the quant was in some arbitrarily defined state. As to a more definite specification of these states, it may be tentatively suggested that an interpretation is to be sought in the variation in the magnitudes, absolute and relative, of the electric and magnetic vectors which characterise the quant. These presumably vary jointly in such a way that the total energy associated with a quant remains constant. The specification of the phase of a quant would involve a specification of the magnitudes and directions of characterising electric and magnetic vectors.

A wave theory can account admirably for the production of interference fringes; but to explain interference it is necessary to do more than this; it is necessary to correlate the observed intensity at different points of a fringe system with the number of quantum switches induced by the radiation. Maxima and minima of fringe systems must ultimately be regarded as points at which the greatest and least number of quanta are actually absorbed (or absorption switches induced), and not merely as points passed by a greater or lesser number of quanta.

A single quantum could not produce a fringe system, yet the idea that this is possible lies at the root of the gravest objection to light quanta. "The bright and dark fringes to which it [a beam consisting of separate quanta] gives rise," Lorentz says, "could never be sharper than those that would be produced by a single quantum." The picture of a single quantum producing a fringe system over which there is a variation in the total number of whole quanta absorbed is purely fantastic, and perhaps points out a direction of possible escape from difficulties.

An explanation of interference must be sought in the joint action of different quanta, and not in the properties of a single one. Experimentally, interference fringes are observed when radiation reaches the point of observation by different paths from a "single point" source. It is important to notice that interference effects do not depend for their appearance on the light originating from a single emitting source, say a single atom. The phase relations necessary are apparently satisfied if the light can be supposed to emanate from a "geometrical point"; there seems to be no evidence that the physical structure of the point (that is the actual emitting systems) must remain constant even over periods comparable in time with the duration corresponding to the coherence length of the wave trains emitted (as is shown in a special case by Thomson's experiment). Though the reason may thus be obscure, even on

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

orthodox classical consideration, from a wave standpoint, the single point source ensures that there shall be some definite phase relation between the interfering wavelets. To account for interference properties there must be some corresponding relation for different quanta originating at the same point. It seems not unnatural or far-fetched to assume that their phase at the point of origin is the same—that the "phase at emission" for similarly polarised quanta, at least, is constant, and hence that different quanta travelling by two paths arrive at a point of observation in the same phase if the path difference is a whole number of "wave lengths," as above defined.

To "explain" interference, however, a further assumption is necessary. It must be supposed that a quantum in a given phase passing an absorbing system, say an atom, tends to modify it (by orientation or otherwise) in such a way as to increase its probability of absorbing a quantum in that phase. It is assumed, in other words, that for absorption to occur, "coupling" must take place between the absorbing system and the quantum; this "coupling" requires a definite relation between the phase of the quantum and the state of the system; and the passage of a quantum gives the system a definite impulse towards the state corresponding to its own phase. Thus the greater the number of quanta in the same phase which pass an absorbing system, the greater the probability of absorption of one of them; the passage of quanta of opposite phase, producing opposite impulses, will diminish the probability of absorption. It must of course be supposed that the effect of the impulse persists, unless the state is modified by external disturbances, for Taylor's classical experiment shows that interference effects still occur even for very weak light.

As to the mechanism involved, it may be tentatively suggested that the impulses are given in the process of scattering. This involves, in general, little transfer of energy, but a transfer of momentum, and probably also changes in direction of the angular momentum associated with the quantum and the absorbing system; this suggests strongly that one of the characteristics of the state which influences the probability of "coupling" and so of absorption is the orientation of the absorbing system with reference to the direction of propagation of the radiation.

"Coupling," of course, it may be mentioned parenthetically, cannot be supposed possible between any quantum and any absorbing system; it need only be supposed to occur in a complete sense when it results in a process of selective or photoelectric absorption; the tendency of a quantum to modify the state of an absorbing system is, however, much more general.

The return to the Newtonian corpuscular theory which the light-quant hypothesis suggests has been frequently noticed; and with

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

it come all the difficulties of accounting adequately for the whole range of diffraction and dispersion phenomena. All these, however, may be regarded as special manifestations of scattering, and in so far as scattering may be explained on a quantum basis, wider developments will cover them also. The view that scattering is explicable on a quantum basis has, it need hardly be mentioned, been inherent in the whole of the present discussion on interference. While the goal is far from having been reached, the work of Compton and others, previously referred to, suggests that it is by no means unattainable.

The above remarks may be summarised as follows. There seems a possibility of explaining interference on a light-quantum basis by attributing phase properties to quanta, and to absorbing systems states corresponding to these phases, and assuming that the general reaction between a system and a quantum is such as to give the system an impulse, whose effect persists, towards the state corresponding to the phase of the quantum. The intensity of radiation at any point, if defined in terms of the number of absorption switches induced, will then depend not only on the number of quanta which pass it, but also on their relative phases. The varying intensity in a fringe system, on this view, does not arise from differences in the numbers of quanta passing, but owing to the phase relations between the quanta arriving at different points being different—in the bright parts tending to bring the atoms into states in which the reaction is a maximum, and in the dark parts a minimum. The nomenclature and general wave theory methods can largely be taken over and applied to the "phase field" surrounding point sources. A more definite picture of the meaning of the "states," and of the nature of the reactions, can only be arrived at by a closer study of the processes of emission and absorption, theoretically and experimentally. Experimental work of the relevant type is as yet in its infancy.

In the following section a few theoretical considerations are brought forward, and some experimental observations briefly noted, which seem to indicate that a more complete and precise explanation of interference on the lines vaguely sketched out above may eventually be possible.

### *The Connection between Quantum Properties and Transition Characteristics.*

Recent successful developments in the application of the quantum theory, and the widening of its scope, have been mainly concerned with the structure of matter, rather than of radiation. Bohr's first postulate, for the fixation of the stationary states of the atom, is, however, intimately bound up with the second

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

postulate, which defines the frequency character of the radiation emitted as a result of a change in the atomic state. While the nature of the processes of emission and absorption are unknown, in so far as a definite picture can be formed of the initial and final states of the atom in which the processes occur, it is possible to form some idea of what must be the properties of the radiation itself, in order that the changes in the radiation field resulting in emission and absorption may be more closely linked up with the changes in the atomic state. Conversely, a knowledge of the nature of the radiation field, and of the changes which take place in it when emission or absorption processes occur, would enable the changes in the atomic state to be deduced.

It is this linking which has been attempted above in reference to energy and momentum. Angular momentum, which can be treated similarly, has not so far been discussed. The correlation of changes in angular momentum of the emitting system with observed states of polarisation has been considered by Rubinowicz, Sommerfeld and Bohr, and developed in considerable detail by these and others. Until the nature of the atomic changes is more definitely known, however—in particular until a more precise meaning can be attached to "inner" and "magnetic" quantum numbers—no conclusive deductions as to radiation can be made. Here it is intended to discuss very briefly the connection which it seems must exist, so that any developments in atomic theory may be utilised for the elucidation of the radiation problem.

On the classical theory the total change in the angular momentum $\Delta P$ in the radiation field associated with a vibrating electron is related to the change in energy $\Delta E$ due to emission or absorption in a manner which varies according to the mode of vibration of the electron from

$$\Delta P = \frac{\Delta E}{2\pi\nu}$$

for a circularly vibrating electron to

$$\Delta P = 0$$

for a linearly vibrating electron. Carrying this over to the quantum theory, in which $\Delta E$ must be put equal to $h\nu$, it is supposed that the angular momentum associated with a quantum may vary from $h/2\pi$ (the unit) to 0. The former is supposed to correspond to circularly, the latter to linearly, polarised light. On the basis of the correspondence which must, in the limit, exist between quantum and classical processes, it has been shown with considerable probability by Bohr that in a normal emission process (that is one uninfluenced by external fields) the azimuthal quantum number $k$ defining the angular momentum of the electron con-

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

cerned in the atom must change by unity. Whether this condition is unavoidable theoretically or not, it does certainly provide a satisfactory selection principle for the occurrence of spectral lines, so that it may be said from an experimental standpoint that in an emission process $k$ changes by unity.

Consider now the simplest possible case of a quantum transition in which the electron switches from one orbit for which $k = n$ to a second orbit in the same plane for which $k = n - 1$. The emitting system loses unit angular momentum, and assuming conservation, this momentum must be associated with the quantum emitted. Now Zeeman effect observations show that the type of polarisation of the emitted light depends on the direction of observation, that is on the direction of emission relative to the planes of the two orbits involved. From this it would seem to follow, adopting the localised quantum view, that the polarisation depends not on the absolute magnitude of the angular momentum associated with the quantum, which is possibly always unity, but on its resolved magnitude in, or at right angles to, the direction of propagation.

This conception clears up some of the difficulties which have hitherto beset the consideration of absorption*. An absorption transition of the normal type, the inverse of the emission transition, involves also a change in $k$ by unity; and this can occur, without any breakdown of conservation laws, whatever the polarisation of the quantum, provided the absorbing system is suitably orientated.

The fact that conservation principles, with reference to angular momentum, may be easily retained in a consideration of processes in which the atomic change is comparatively simple, and relatively understood, makes it seem probable that they will hold also in the more complicated transitions which occur in the presence of external fields.

A large number of observed phenomena connected with the Zeeman effect may be correlated by assigning to the terms, as well as electronic azimuthal quantum numbers $k$, magnetic quantum numbers $m$ which define the atomic angular momentum in the direction of the applied magnetic field. When this quantum number changes by unity (as well as $k$) the light observed is circularly or linearly polarised according to the direction of observation; but transitions also occur for which $m$ does not change, and the light corresponding to these transitions is linearly polarised, with its electric vector in the direction of the applied magnetic field. Adopting the light-quantum view, this seems to suggest that, somewhat as on the classical theory two different mechanisms—namely, circularly vibrating electrons, observed in a special direction, and linearly vibrating electrons—may give rise to plane polarised light, plane polarised quanta may be of two different types. This dual nature

* Cf. Bohr, *l.c.* p. 41.

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

of "plane polarised transitions" is, of course, remarkable whatever view of radiation is adopted, and it emphasises the gaps in the picture of transitions from the atomic side. Particularly it makes it hazardous at present to attempt to define any more precisely the exact relation between the directions of the axis of angular momentum, of propagation, and of the electric and magnetic vectors characterising quanta of a given state of polarisation.

That orientation occurs in magnetic fields is shown absolutely definitely by the experiments of Gerlach and Stern, and that the polarisation character of the emitted light depends on orientation necessarily follows from the Zeeman effect. It is desired to emphasise here the importance of orientation in connection with absorption, which becomes clear from an examination of the experiments of Wood and Ellett* and others, on the effect of magnetic fields on the polarisation of resonance radiation. An analysis of their results† shows that certain absorption transitions may be entirely prevented by appropriate orientations of the magnetic fields. The probability of quanta in a definite state of polarisation being absorbed thus depends essentially on the orientation of the absorbing system.

The experiments on mercury vapour suggest even further possibilities. The resonance radiation with this was observed to be polarised even in the complete absence of external magnetic fields to an extent which seems to indicate that the absorbing systems were orientated in a definite way relative to the incident beam. With the experimental results available at present it would be unwise to speculate dogmatically; but the experiments certainly suggest strongly that absorbing systems may be orientated by the influence of a beam of radiation traversing them; the only mode of interaction, moreover, is that involved in scattering, which, in the case considered here, with the incident radiation corresponding to a "natural frequency" of the absorbing system, is of the "enhanced" type.

From the experiments, then, emerges the certainty that absorption depends on orientation, and the possibility that this orientation may be affected by radiation itself.

Considerations of the above type suggest the wide possibilities there are to be explored before hope of explaining interference on a light-quantum basis should be given up, or principles of conservation abandoned. The question of the influence of quanta in different phases—essential for a full explanation of interference—can only be tentatively and speculatively considered. "Coupling" and absorption of a quantum of a definite type, coming from a definite direction, will on the present view only occur, for a definite phase,

* Wood and Ellett, *Proc. Roy. Soc.* 103, 396 (1923); *Phys. Rev.* 24, 243 (1924).
† See Joos, *Phys. Zeit.* 25, 130 (1924).

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

if the atom is in a definite corresponding state; moreover this state will vary according to the phase of the quantum. The state may depend partly on orientation, but not wholly—Weiner's experiment alone seems to show this—but precisely what are the variables which define it is still obscure.

Orientation, however, by no means exhausts the possibilities. Orientation phenomena seem to be primarily magnetic in character. Now a quant is not characterised simply by a magnetic vector, but by electric and magnetic vectors jointly, whose directions and magnitudes define not only the state of polarisation but also the phase of the quant at any point of its path.

An electron orbit in an atom may also be regarded as characterised by two vectors, one of which—the one so far considered—defines its orientation and magnetic moment in a particular direction. In general, however, an orbit will be characterised by a second vector defining its electric moment, whose axial direction will be given by the line joining the orbit's "electric centre of gravity" to the nucleus of the atom. It seems as if this may be of equal importance with the magnetic vector.

Both the electric and magnetic moment of the orbit-nucleus (or orbit-core) system may be modified by a passing quant, and in order that a quant in a given phase may be absorbed it is supposed that they must have an appropriate value.

The necessity, in connection with interference, for supposing that emission occurred at constant phase, while absorption of quants in any phase was possible, seemed at first sight to run counter to the demands of thermodynamics for the strict reversibility of individual processes. The absorption of quants in any phase by suitably "modified" systems is now, however, seen not to be thermodynamically incompatible with the constancy of phase at emission from "unmodified" systems.

The conception of the electric vector, moreover, strongly suggests a clearer outlook on the difficulty of the dual nature of "plane polarised transitions" referred to above, circularly polarised components (in transverse observation with the electric vector perpendicular to the field) corresponding to sudden transition changes in the magnetic, and plane polarised components (in transverse observation with the electric vector parallel to the field) to changes in the electric vector.

The Stark effect becomes of equal importance with the Zeeman effect as a key to the whole problem, but the working out of the details must be left to the future.

It has been shown here that it seems possible to apply the law of conservation of angular momentum as well as of energy and momentum to individual quantum emission and absorption processes, and that this may enable the properties of radiation to be

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

eventually more precisely defined. The importance of an electric vector defining orbit systems has been emphasised. Some of the factors which would be involved in an explanation of interference in terms of spatially localised linearly directed quanta, to which the previous arguments led, have been considered, vaguely and speculatively. Vague speculation may however be justifiable if the only alternative is theory involving the complete abandonment of fundamental physical generalisations, and the substitution of purely formal concepts.

*Summary.*

It is shown that, assuming conservation of energy and momentum in individual transitions, radiation must be regarded as propagated by linearly directed quants. Evidence is brought forward in favour of the view that these quants are spatially localised longitudinally as well as laterally. As these conclusions seem unavoidable, an attempt is made to see if there is any possibility of accounting for interference effects in terms of quants possessing periodic properties.

The idea that a single quantum can produce interference effects is untenable. The conception of the phase of a quant is introduced, and it is supposed that atoms may absorb a quant in a given phase provided they are in a "state" corresponding to that phase. Considering radiation emanating from a point, it is shown that a tentative explanation of interference may be obtained if the quants have a constant phase at emission, and if they give atoms at any point an impulse towards the state corresponding to their phase at the point. According as these impulses reinforce or oppose each other, bright or dark parts of a fringe system are obtained. Practically the whole nomenclature and method of the wave theory may be taken over and applied to the quant phase field surrounding an emitting source. Essentially, on this view, an explanation of interference is sought in terms of different quants, and the dark and bright parts of a fringe system are to be explained, not in terms of different numbers of quants arriving at them, but in different phase relations of quants which do arrive.

Quants are characterised by a magnetic and electric vector, whose magnitudes and directions define the state of polarisation and the phase. Electron orbits may also be regarded as characterised by two vectors in terms of which it seems as if the "state" may be specified.

The relation between transition character and type of radiation emitted is finally considered and it is shown that the evidence so far available renders plausible an explanation of interference of the kind put forward. Much further experimental work, particularly



https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press

in connection with the Stark and Zeeman effects, is, however, necessary, before sufficient precision can be given to the views put forward to make them satisfying. On the other hand, it seems premature to suppose that only a formal treatment is possible of the physical phenomena involved.

I would like to thank in particular Mr R. H. Fowler and Mr C. T. R. Wilson for helpful criticism and discussion of special points; I would also like generally to express my feeling of indebtedness to these, and many others, in conversation with whom have originated in part some of the ideas put forward.

https://doi.org/10.1017/S0305004100003303 Published online by Cambridge University Press