SHANTI SWARUP BHATNAGAR MEMORIAL LECTURE, 1966

SOME PROPERTIES OF RADIATION

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It is a great honour to be invited by the National Institute of Sciences to give the Bhatnagar Memorial Lecture. My thoughts go back to the day when the foundation-stone of the building of the Institute was laid by Jawaharlal Nehru on the 19th April, 1948. Dr. Bhatnagar was the President of the Institute at the time; and we owe more to him than to anyone else for the present site, so centrally located, and the building of the Institute. Bhatnagar was a most remarkable person, and his energy, amiability and resourcefulness were unbounded and inexhaustible. He was an eminent chemist and a great teacher but, above all, he was the main architect of the chain of national laboratories that we have in the country today. He worked for them with a devotion and zest that was unmatched. Dr. Bhatnagar will be long remembered as one of the great pioneers of Indian science. Many of us had the privilege and good fortune of knowing him personally. He was a warm and affectionate friend, always willing to do all he could to help scientists, young and not-so-young, in need of facilities and encouragement. His hospitality was proverbial.

It is with feelings of gratefulness that I take this occasion to pay homage and tribute to his memory for his many unique and pioneering services to the cause of Indian science.

Philosophers in India, Greece and elsewhere have speculated about the atomistic constitution of matter since the dawn of civilization, but it is only during the last two hundred years or so that indisputable arguments and experimental evidence have been provided to establish the reality of atoms. The atomic concept constitutes the most important element of the scientific view of nature. Niels Bohr giving the Nobel Lecture in 1922 began with the following words: 'The present state of atomic theory is characterized by the fact that we not only believe the existence of atoms to be proved beyond a doubt, but also we even believe that we have an intimate knowledge of the constituents of the individual atoms.'

It is well recognized that the remarkable stability of atoms and molecule, which is necessary for the very existence of any experimental science, is totally inexplicable in terms of classical physics. According to classical physics the moving electrons in an atom would radiate energy, and in a time of the order of 10^{-10} sec the electrons would fall into the nucleus emitting energy in the form of radiation. It is to 'quantum mechanics' that we owe an explanation of the stability of atoms: it is the Planck's constant, as it were, which stands between us and instantaneous annihilation.

A fundamental concept in quantum mechanics (and hence in science generally) is that of the 'state' of a system. Recall, for instance, J. D. Bernal's (1967) recent definition of life: 'Life is a partial, continuous, progressive, multiform and conditionally inter-active, self-realization of the potentialities of atomic electron states.' The importance of the concept of the state arises because of the superposition principle which allows states of an atomic system to be superposed to give new states. Superposition of states makes no sense whatsoever in classical physics. The superposition principle and the Heisenberg's uncertainty principle go together. Let me add parenthetically that in classical physics we have superposition of waves but not of *states*. It is unfortunate that the concept of state finds no place in the high school physics; and even in undergraduate courses it is given not more than a passing reference.

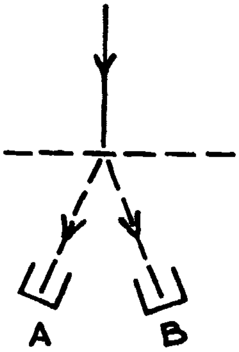

FIG. 1.

The physical basis of the superposition principle is the wave-particle duality. This leads to an inescapable unpredictability in the description of natural phenomena on the atomic scale. It is statistical results only that can be predicted. The inherent uncertainty in the description of events on the atomic scale can lead to a somewhat unexpected unpredictability as regards macro-events, i.e. events on the scale of things we handle in our everyday experience. For instance, consider a single photon passing through a diffraction grating. It is impossible to predict in which direction the photon will emerge from the grating: whether it will trigger the counter at A or the counter at B. We can only predict the probability. for the two events, but it is impossible in the nature of things to know beforehand with certainty whether the photon will trigger the counter A or the counter B. Instead of the two counters we could have fuses firing two guns. We could then *not* know whether the photon will fire the gun A or the gun B. Take another example. We are subjected to a continuous bombardment of cosmic rays. Even if we knew all about the intensity and energy distribution of the rays, we could not predict with any certainty whether a given cosmic ray particle passing through our body will produce a mutation or not. We can only predict statistical averages, but not what will happen in an individual case.

It is interesting to observe that the *stability of atoms and molecules is necessary for the process of thinking itself.* Memory, and thinking, in its ultimate analysis, is probably molecular in origin. If the thermal motions of the 'molecules' in the brain are not to distort or destroy the 'thought' in the brain, and if we are to be able to hold steady a thought, then the excited states of the molecules corresponding to the thought process must have an excitation energy sufficiently above the energy of random thermal motion. We could perhaps say with some justification that the very fact that we can 'think' demonstrates that the Planck's constant exists.

The concept of the absolute indistinguishability of particles of the same kind, e.g. electrons, photons and so on, is a fundamental concept in quantum mechanics. It is generated, as it were, by the very nature of the quantum formalism. Its consequences are of the utmost significance and wide applicability. It is this principle of indistinguishability which accounts for the complete system of the chemical elements and the phenomena of chemical valency giving rise to all the richness and variety of the chemical world. It may be observed that the concept of absolute indistinguishability of similar particles is foreign to classical physics, as in classical physics particle-trajectories are sharply defined, and, therefore, the space-coordinates of the particles at some given instant of time could themselves be used as 'labels' to identify the particles for all time. However, the very existence of the Planck's quantum of action implies a renunciation of precise space description of the motion of a particle. For, if a sharply defined particle-trajectory were permissible in quantum mechanics, it would mean that the angular momentum about any given point could be arbitrarily and continuously varied by merely displacing the reference point, leaving unaffected the state of motion of the particle. The existence of the quantum of action imposes a certain element of mutual exclusion as regards the precise knowledge or observation of physical quantities relating to an atomic system. This is expressed by the Heisenberg principle of uncertainty which applies to measurements of physical quantities in the case of a particle as also for a field (e.g. measurements for electric and magnetic field intensities). The principle of uncertainty has been given a philosophical and epistemological meaning, notably by Bohr, under the name of the principle of complementarity. The principle of the superposition of states which constitutes the basis of the mathematical formulation of quantum mechanics has its physical roots in the principle of uncertainty.

The principle of uncertainty is a direct consequence of the fact that every entity in nature is characterized by the wave-particle duality. This is the fundamental 'mystery' of quantum mechanics, and it cannot be explained away. It seems likely that, apart from the cosmological, all physical, chemical and biological phenomena would eventually be accounted for in terms of the wave-particle duality.

Atoms in undergoing transitions from states of higher to lower energies radiate photons. The usual process is a single-photon transition described by the relation: $E_2 - E_1 = \hbar\nu_{21}$, but under certain conditions multiple-photon processes can also occur satisfying the energy conservation relation: $E_2 - E_1 = \hbar(\nu + \nu' + \nu'' + \ldots)$.

A radio transmitter is a powerful source of low-energy photons—a transmitter operating at a wavelength of 100 m and a power of 100 kW radiates a flux of the order of 10^{32} photons per second. There is a fundamental difference between a radiating atom and a radiating antenna. In the case of an antenna, the wavelength of the emitted radiation is of the same order as the length of the antenna; the radiation spectrum consists of a fundamental frequency and its harmonics; and the emitted radiation is coherent, that is the emitted photons travel together in phase. (The situation in all these three respects is analogous to what it is for an organ-pipe producing sound waves—*phonons*.) An assembly of excited atoms, on the other hand, emits radiation (spontaneous emission) of wavelength several orders of magnitude larger than the size of atoms; the radiation spectrum consists of frequencies which obey the Ritz combination law and there are no fundamental frequencies and their harmonics; and the radiation is non-coherent. Planck in 1918 delivering the Nobel Lecture said: 'The fact that the quite sharply defined frequency of an emitted photon should be different from the frequency of the emitting electron must seem to a theoretical physicist, brought up in the classical school, at first sight to be a monstrous and, for the purpose of a mental picture, a practically intolerable demand.'

An atomic system is totally inexplicable in terms of classical physics; but when a large number of electrons oscillate in phase in an antenna under the influence of applied alternating field, the system behaves classically. We can understand this situation in the light of the uncertainty principle. A plasma, like a radiating antenna, can produce coherent radiation (Ginzburg and Ozernoy 1966).

INTERFERENCE OF PHOTONS, COHERENCE EFFECTS

In the usual interference and diffraction phenomena (variation in the intensity of light with the location of the point of observation) observed with light, we know, it is not two different photons that interfere, but what we observe is a pattern (probability distribution) arising from the interference of a photon with itself. Yet, under certain conditions correlation effects (relation between intensities at the different points) between photons (as also between particles of the same kind) can occur. These we proceed to discuss briefly.

Recently Brown and Twiss (1956) have demonstrated experimentally a most remarkable 'correlation effect' between different photons. It is a consequence of the Bose statistics obeyed by photons. To illustrate how the effect arises, let us consider two independent light sources S_1 and S_2, and the correlation we study is the simultaneous detection of two photons, one in counter O and the other in counter X, as the distance OX is varied (Feynman 1961).

The photon-coincidence could occur in four ways:

(i) Both photons come from S_1, (ii) come from S_2, (iii) O receives from S_1 and X from S_2, and (iv) O receives from S_2 and X from S_1. If we denote the respective probability amplitudes by a_1, a_2, a_3 and a_4, then we have

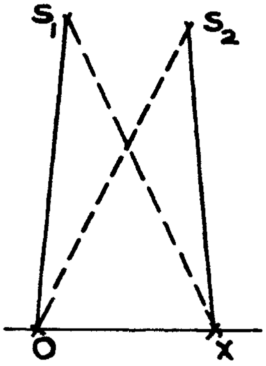

FIG. 2.

$$P = |a_1|^2+|a_2|^2+|a_3+a_4|^2.$$

The last term contains an interference effect. (For fermions the last term would be $|a_3-a_4|^2$. The probability expression implies that, whereas we can distinguish between processes (i) and (ii) and, therefore, add the corresponding probabilities and not amplitudes, we cannot distinguish between (iii) and (iv) so long as, in accordance with the uncertainty principle, OX is not too large compared to OX_1 given by

$$d \cdot \frac{h\nu}{c} \cdot \frac{OX_1}{D} \sim h,$$

$$OX_1 \sim \frac{D}{d} \lambda,$$

where

$$S_1S_2 = d_1 \text{ and } S_1O = D.$$

It is apparent that the correlation effect described above can be employed to measure diameter of stars; and this has been done by Brown and Twiss. Note that if we have only one receiver then no coincidence pattern is observed as the relative phase of sources S_1 and S_2 is random and fluctuating with time.

The Boson character of photons tends to favour a distribution in which more than one photon occupies the same state. This will happen even in the case of thermal radiation (black-body radiation), as was pointed out about ten years ago (Kothari and Auluck 1957). It would, perhaps, be not wrong to say that the possible implications and observational, physical and astrophysical consequences (multiphoton effects) of this pairing or bunching together of thermal-radiation photons have not yet been fully explored. The average number (S) of photons, associated on account of Bose correlation with a given photon in the case of black-body radiation, is given by

$$S = \frac{f(2)}{f(3)} - 1 \sim 0{\cdot}3685.$$

Also, if $D(r)$ be the photon density (number of photons per unit volume) at a distance r from a given photon, then $D(r)$ tends to $2n$ for r tending to zero, where n is the average photon density for the assembly (total number of photons in the assembly divided by its volume). The increase in the average density for r tending to zero is compensated by a small general decrease in the density throughout the volume of the assembly. This is another version of photon bunching or lumping together.

Let us now confine ourselves to the case of photons lying in the momentum range k, $k+dk$, we have

$$S = n(k) = \frac{1}{e^{hck/RT} - 1},$$

where $n(k)\,dk$ is the number of photons in the range k, $k+dk$.

For $$hck \gg RT, \quad S \sim \exp\left(-\frac{hck}{RT}\right)$$

and for $$hck \ll RT, \quad S \sim \frac{PT}{hck}.$$

This brings us to masers and lasers (maser/laser is acronym for microwave/light amplification by stimulated emission of radiation). The subject started in the early 1950's and the 1964 Nobel prize was awarded to Basov, Prokhorov and Townes for their work in this field.

The theory and applications of lasers constitute a major chapter in quantum electronics. The atomic hydrogen laser is likely to replace the cesium time standard. It has short-term and long-term stabilities of 1 in 10^{13} and 1 in 10^{12} respectively. A laser source working at visible frequencies resembles in many ways a radio transmitter. In recent years there have been produced coherent tunable oscillators, amplifiers, wave guides, ultrashort light pulse generators and so on. The laser provides a powerful tool for optical research, Raman spectroscopy and many diverse fields including biology and metallurgy. Powerful laser beams can puncture metals and are likely to find important military applications. Holography is another field of laser application. The laser has made it possible to produce an optical radar which in some applications has advantages over the usual micro-wave radar. By mode locking a pulse laser it has been possible to obtain light pulses of ultrashort duration (10^{-12} sec) possessing a power as high as 10^{12} W/sq cm which corresponds to a field of 10^7 V/cm.

The active medium in a laser may be a solid, as gas, or a liquid. There are several possible ways of exciting a laser. The most common method is to employ a suitable beam of light—this is called 'optical pumping'—electric current, and bombardment with electrons are also employed with some substance. Recently chemical reaction (molecular dissolution) has also been used to excite a laser.

It is interesting to note that some recent astronomical observations on the radio emission from OH radical present in inter-stellar space indicate that some kind of maser action may be occurring on a gigantic scale in the galaxy. (Litvak *et al.* 1966). This has led to speculations about the use of OH radio radiation for inter-stellar communication (Barrett 1967).

For a thermal source at temperature of 10^4 deg, $n(k) \sim 10^{-3}$ for light of visible frequencies. With a laser (non-thermal source) it has been possible to realize light beams having an 'effective temperature' of the order of 10^{20} °K and higher. It is this fantastically high effective temperature that gives rise to several unexpected phenomena with lasers (and many have yet to be discovered). A photon beam corresponding to a photon density of 10^{20} and photon energy of 2 eV (for ruby laser $\lambda = 0{\cdot}69\ \mu = 1{\cdot}78$ eV) has an electric field of $2{\cdot}7 \times 10^7$ V/cm. (A plane wave with a flux density of 1 MW/cm^2 has an electric field of amplitude $2{\cdot}74 \times 10^4$ V/cm.)

Bystrova *et al.* (1967) have been able to obtain ionization of Xe and Kr gases with neodymium laser: $\lambda = 1{\cdot}06\ \mu = 1{\cdot}18$ eV; electric field $\sim 4 \times 10^7$ V/cm which corresponds to an emission intensity of 10^{31} photon/cm^2. The ionization potential of Xe is 12·13 eV and of Kr 13·996 eV. The experimentally observed value of the ionization probability is proportional to the ninth-power of the emission intensity. This is much less than the ratio of ionization of potential to the photon energy ($h\nu$) and is 'evidence that an appreciable contribution is made to the ionization probability by transitions between bound states, and that the radiation field has a strong influence on these states'. More theoretical and experimental work is necessary to obtain a clear understanding of the phenomenon of breakdown of gases under action of laser radiation.

The experiments on multiphoton phenomena with lasers have stimulated the study of multiphoton effects generally. Coherent Raman radiation and also stimulated two-photon transition between discrete atomic states have been produced. The (forbidden) transition from ^3S to ^1S (ground state) in helium, emitting two photons, has been recently observed (Lipeles *et al.* 1965). An interesting type of double quantum transition between the Zeeman sublevels of an atom brought about by virtual absorption and successive re-emission of optical photons has been detected by Happer and Mathur (1967).

Mesons are Bosons, and here there is a possibility that under suitable conditions 'laser type' phenomenon may be exhibited by a beam of mesons. (It may become possible by subjecting excited nuclei to the action of a meson beam to produce an intense monochromatic beam through laser-type amplification.)*

NON-DEGENERATE RADIATION

It is important to ask the question whether there occurs in nature the non-degenerate case for radiation. This question has acquired an added interest in view of the recent astrophysical work of Wildt (1966) on the thermodynamics of the grey atmosphere. This work has been inspired by the progress made in the study of irreversible thermodynamics. There appears no obvious physical reason why non-degenerate radiation should not occur in nature. It is possible that non-degenerate radiation may partly account for the departure from black-body radiation met with any certain astrophysical states, but at the present time it is to be regarded as an open question. In this connection it should be mentioned that non-degenerate radiation should not be confused with dilute radiation (Kothari and Singh 1941).

The recent discovery that the universe is filled with micro-wave radiation constitutes a landmark in astrophysics. The micro-wave background radiation observed in the frequency range $(1–100)\times 10^9$ cycles/sec corresponds to a black-body temperature of about 3° K. This radiation, according to the theory of Dicke, has its origin in the degradation of the original very high temperature radiation present at the time when the universe, some 10^{10} years ago, was contained in a relatively tiny volume. It is of some interest to ask the question whether the micro-wave radiation is completely degenerate or non-degenerate? The answer must await careful experiments on the intensity distribution micro-wave radiation. (It is interesting to observe that the temperature of the cosmological micro-wave background is not the same in all directions. It has been recently found that the temperature is higher by about 0·016° K in a direction roughly pointing towards the area in the sky which contains the biggest concentration of quasars with the biggest red shifts.)

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* Also it may be possible using intense optical laser beams to illuminate gamma emitting radio-active nuclei to modulate the frequency of the gamma radiation.

EFFECT OF RADIATION ON LAMB SHIFT

A landmark in quantum electrodynamics was the far-reaching discovery by Lamb and Rutherford (1947) that for the H-atom the $^2S_{\frac{1}{2}}$ and $^2P_{\frac{1}{2}}$ levels are not coincident as required by Dirac's equation for the H-atom, but the ^2S level is higher than the ^2P level by about 10^9 cycles per sec. The effect is caused by the interaction of the electron with the 'vacuum field'. It is of the order $\alpha^3 R_y$, where α is the fine structure constant. The most recent experimental value for the Lamb shift for the H-atom is 1058·05±0·10 Mc/sec; and the latest theoretical value is 1057·499±0·11 Mc/sec (Soto 1967). The cause for the small discrepancy between the experimental and theoretical values is not quite understood.

It is an obvious extension of the theory of the Lamb shift to include the effect on the level-shift of the presence of external radiation (Kothari and Auluck 1948). The radiation effect is likely to be of considerable astrophysical significance. Recently a preliminary experimental demonstration of the displacement of energy levels of atoms by light has been provided by A. Kastler and his associates using a development of the 'optical-pumping' techniques (Kastler 1963). (Also see Aleksendrov (1966) for observed shift for K atom.)

We shall not give here the usual quantum mechanical derivation of the level-shift caused by radiation (Auluck and Kothari 1952 and Reiss 1966) but content ourselves with presenting an intuitive classical picture of the phenomenon. This becomes possible because the radiation-induced level-shift is proportional to the intensity of the incident radiation. And for convenience of theory we may assume that the intensity tends to be infinitely large in which case the quantum effects of radiation can be ignored—the radiation field then is no longer a 'small system' but can be regarded as a 'large system' described classically.

An electron placed in a radiation field acquires an additional kinetic energy equal to $2\pi \frac{e^2}{mc} \frac{\omega^2 I}{(\omega_0^2-\omega^2)^2}$ where ω_0 is the natural frequency of the 'electron oscillator', ω is the frequency of the incident radiation which has intensity I $(=cE^2/4\pi)$; m is the rest mass of the electron. As the Rydberg constant is proportional to the electron mass, the frequency increase of the atomic spectral lines is given by

$$\frac{\Delta\nu}{\nu} = \frac{2\pi e^2}{m^2c^3} \frac{\omega^2}{(\omega_0^2-\omega^2)^2} I \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \text{(A)}$$

For the case of $\omega \gg \omega_0$, we have

$$\frac{\Delta\nu}{\nu} = \frac{2\pi e^2}{m^2c^3} \frac{I}{\omega^2} = \frac{e^2}{2\pi m^2c^5} \lambda^2 I.$$

For a 10-cm micro-wave power of IMW in a wave guide of 30 cm^2 cross-sectional area, $\frac{\Delta\nu}{\nu} \sim 10^{-4}$; and this should be rather easily detectable.

We may notice that the level-broadening due to the motion of the electron caused by the incident field is of the order of $\frac{e}{mc}\left|\frac{\omega E}{\omega^2-\omega_0^2}\right|$. The ratio R of the level-shift to the level-broadening is, therefore, given by

$$R \sim \frac{e}{mc^{3/2}}\left|\frac{\omega}{\omega^2-\omega_0^2}\right|\sqrt{I}$$

which for the above numerical illustration gives $R \sim 1$.

The experimental results of Kastler (1966) and his associates on the nuclear magnetic resonance line of ^{199}Hg appear to be in qualitative agreement with the above expression, but a quantitative comparison does not seem possible yet.

In conclusion, I would like to draw attention to the relative neglect of the study of astrophysics in our country. At one time astrophysics was the high peak of Indian science. Who does not know of the work of Saha? If the significance of a discovery is to be judged by the fruitfulness of its consequence, then the work of Saha on thermal ionization must be regarded as one of the greatest discoveries of all time. There are many exciting things in astrophysics today. There is the problem of quasars, of the cosmological micro-wave radiation, the influence of motion and gravitation field on temperature (relativistic thermodynamics), of the nature of the gravitational force itself and the possibility of producing gravitational waves; the problem of matter and anti-matter, and so on. Physics and astrophysics have a very close and fruitful interaction. I do hope that in the years to come there would be greater interest in the study of astrophysics than has been the case in the immediate past. It is important that we have in the country at least one or two centres of astrophysical work compared to some of the international centres.

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