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Some Light on Physics

an Inaugural Lecture delivered
at the University College of Swansea
on 14 March, 1972

by
PROFESSOR COLYN GREY MORGAN
M.Sc., Ph.D. (Wales)
Department of Physics

GWEDDW CREFFT HEB EI DAWN

UNIVERSITY COLLEGE OF SWANSEA

"Are not gross Bodies and Light convertible into one another, and may not Bodies receive much of their Activity from the Particles of Light which enter their Composition ?"

Newton, Opticks, (4th Ed. 1730)

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I. Physics

I have it on excellent authority (1) that one of the first duties of a professor is to exaggerate a little of the importance of his subject and his own importance in it. Professors of Physics find this exceedingly difficult to do on two scores. Firstly there is no denying that physics is very important indeed so that overstatement can only sound contrived and artificial with the risk that perfectly valid statements about physics are greeted with disbelief. Secondly, natural modesty has to be overcome, and, as is well known, all physicists are diffident.

I shall attempt to set these difficulties aside in this inaugural lecture. It seems appropriate, since my appointment is to a Personal Chair of Physics in the University of Wales, to give you a personal account of some of my interests in physics, to show you how they have arisen, and to see where and how they impinge on Society. But first I must say something of physics and a little of its development, and too, a few words about physicists.

Physics is the most basic of natural sciences. The word physics means nature and thus physics, in the original sense of the word, means the study of nature in general. Nowadays we consider it as the science through which we seek to understand the behaviour of matter and radiation. It sets out to establish laws to explain and to predict how matter and energy interact at the most fundamental and universal levels. Physics does this with the aid of mathematical expressions which embody, with great conciseness, the rules of nature connecting whole ranges of phenomena which, at first sight, appear unconnected, even isolated. Physics is rooted in experiment, that is, in observation and quantitative measurement of the highest accuracy. The business of physics then is to describe natural phenomena as consequences of the smallest number of independent postulates which are capable of experimental verification.

Our first conscious awareness of the physical word comes with our senses of touch, of sight and of balance. It is through these that we are led to wonder and speculate about the nature of our surroundings. Our earliest experiences of nature are with the solidity of the earth on which we can stand, with the freely flowing waters on which we cannot stand and with the air and vapours through which we can move unimpeded. These material substances obviously have different physical properties which distinguish the one from the other and which enable us to make a primitive classification of matter into solids, liquids and gases. But these are tangible properties, quite unlike the ethereal quality of the light reaching us from the stars and sun and the sensation of warmth which we can perceive even without vision or touch. Nevertheless these too form a definite part of nature.

While awareness of these qualities follows from everyday experience the concept of physical force—a constraining influence, that which preserves a certain order of things, does not arise so easily. Because of our environment the earliest natural force to gain recognition was that of gravity, followed in turn by magnetic and electric forces.

Our present knowledge of these grew out of four branches of enquiry which served as the spring-board for modern physics. Firstly, Mechanics, the study of moving objects from falling stones to celestial bodies, placed on a quantitative basis by Newton, Galileo and Kepler. Secondly, Optics, the study of light and vision, where again, Newton made major contributions, together with Huygens, Young and Fresnel. Thirdly, Thermodynamics, the study of heat. This was a late nineteenth century development guided by Maxwell, Clausius, Boltzmann, Planck and Gibbs, and, fourthly, Electromagnetism, the study of the electric and magnetic properties of matter, to

which Faraday, Oersted and Maxwell contributed so much.

It was not until the latter half of the nineteenth century that the connections between these four fields of learning coalesced to form the basis of physics as we know it today. Before this time, physicists, a name* which appears to have been invented by the Cambridge historian and philosopher George Whewell in 1840, had suspected, but had not established, the cross-links which proved to be so fruitful in the present century.

Heat became recognized as the random motion of tiny particulate matter—atoms and molecules. Light could be described as an electromagnetic wave. These waves were in turn associated with the vibrations of even smaller particulate matter—electrons—within the atoms. Furthermore the very essence of electricity was identified with these electrons which possessed, in addition to their mass, a conceptually new characteristic—charge—which was irreducible. Electric and magnetic effects were recognized as manifestations of the charges, the nature of the effect depending upon their motion.

Underlying these advances was the concept of classical fields—a kind of tension or stress which exists in empty space. It reveals itself by producing forces which act on material bodies lying in the space occupied by the field. The gravitational field has the special property of being able to act on all material bodies in a region of space while the electromagnetic field acts only on charged bodies.

All the cross-links had effectively been established by the last decade of the nineteenth century and the stage was set for the major developments of the quantum theory of radiation and the atomic theory of matter. By 1911 Rutherford, basing his work on the newly discovered

*As might be expected, the Greeks had a word for it. Thus Strato, who followed Aristotle and Theophrastus as head of the Lyceum, was known in antiquity by the special name of "The Natural Philosopher". Strato "excelled in all branches of learning but most of all in that which is styled the philosophy of nature, a branch of philosophy more ancient and serious than the others". (2)

phenomenon of radioactivity had confirmed Perrin's view, put forward ten years earlier, that the atom was nuclear.

The most complex matter could be broken down into individual atoms. Each atom was basically made up of equal numbers of but two types of electric particles—massive positively charged protons located at a central nucleus around which negatively charged electrons circled much as the planets orbit the sun in our solar system, but, of course, on an infinitesimally smaller scale. The number of protons and electrons fixed the identity of an atom. Perturbation of the electrons from their orbits led to the production of light characteristic of the atom and so to a new means of identifying the elements. Within two years Bohr had succeeded, by an heretical combination of classical electromagnetism and Planck's quantum ideas, in advancing knowledge of the outer electronic structure of the atom to the point where he was able to predict the colours of the light emitted from hydrogen and ionized helium. He had reduced the description of the atom to a set of numerical constants and a single quantum number. His hypotheses were greeted at first with scepticism, but this was removed when his calculations received the most precise and timely verification in brilliant experiments carried out at Manchester by the man who later became the first professor of physics and head of this Department—E. J. Evans of Llanelli. It was a turning point in the history of science and linked atomic physics with astrophysics.

This nuclear atom with its orbiting electrons was a satisfying picture of nature on her smallest scale. Its very simplicity was appealing. It lent support to the comfortable concept of the basic building blocks of matter—just two of them, the proton and the electron, with the means of producing light by quantum jumps between orbits. Here lay the understanding of how atoms united to form molecules, and of how molecules interacted chemically.

This period of unification also marked a parting of the ways. Having established the binary nature of the atom and demonstrated their ability to split it, that is, to ionize

it into its electrical components, physicists began to look at the properties of both components, to see how they interacted with matter. Here began the divergence into nuclear or elementary particle physics, concerned with the inner structure of the nucleus, and atomic or ionization physics devoted to studying the behaviour of atoms and molecules in collisions with electrons and with radiation.

On these two broad fronts physics quickly ran into some pretty traumatic experiences as unpalatable and apparently contradictory experimental facts emerged. The simple binary picture of the atom did not remain intact for long. New phenomena were discovered and old ones revived which seemed to rob the electron of its particle-like nature. It displayed the light-like characteristics of diffraction and interference. Its behaviour inside atoms and in certain conditions when freed from the binding influence of the nucleus was better described mathematically in terms of waves, but not waves in any material substance, but rather probability waves.

Conversely, the well established wave-like nature of light was once more brought into question by the way it was found to interact with metals to produce electrons. This called for an interpretation of light as particles just as Planck had proposed. These quanta, or photons as they are now called, nevertheless appeared to retain some wave-like character inasmuch as they could be assigned a frequency or wavelength.

The physicist's concept of accuracy of measurement, the corner-stone of his scientific method, received a severe jolt on the atomic scale with the realization demanded by the quantum interpretation of light that the more precisely one wished to measure say the energy of a photon the more uncertain one became of how long it retained that energy. Similarly if one wished to know accurately the momentum of an electron the more uncertain one became of where it was. Locating electrons and photons in space and time could be achieved only by applying the laws of probability. It is as though nature had entered into a conspiracy to frustrate any really close examination. This curious indeterminate behaviour of atomic matter has been expressed in an Uncertainty Principle by Werner Heisenberg. It is a very general law of quantum mechanics with profound philosophical implications.

But to remove any misconceptions concerning the importance that physicists attach to precision of measurements that may have arisen from these remarks, I would hasten to say that Heisenberg formulated his principle in a very precise way so that we know exactly how uncertain we are. The limits of accuracy are, by any normal standards, very fine indeed. The Uncertainty Principle sets a limit to the applicability of the classical mechanics, and together with the established particle-wave duality of matter and of radiation, forms the basis of quantum mechanics in which, strange though it may seem, particles behave like waves and waves like particles. However uncomfortable one feels at this afront to common sense on the part of nature one must recognize that this behaviour on the atomic scale seems to be an undeniable part of our Universe.

There were corresponding and equally disturbing developments stemming from studies of the propagation of light, principally due to Einstein, which destroyed any intuitive grasp that one felt of space and time and of mass and energy. No longer could it be said that two observers in relative motion looking at the same occurrence would agree as to the place and time at which it occurred. The concept of simultaneity was destroyed. Nor would the length of an object appear to be the same to two experimenters in relative motion. However, like the quantum effects which are manifest only at the extremes of smallness the relativistic effects occur only at the extremes of velocities—approaching that of light itself. It is for this reason that we are not aware of them in our every day experience. Nevertheless everyone is surely aware, nowadays, of their consequence, namely that mass and energy are the same thing, merely different forms of matter, to be transformed into one another given favour-

able circumstances. Einstein's famous equation $E = mc^2$ where m is the mass, c the velocity of light and E the energy released if the mass is annihilated is familiar to everyone with its realistic demonstration in atomic weapons and in the generation of nuclear energy. It is virtually impossible to overestimate the consequences of this equation on our pattern of life.

Difficulties have arisen on the elementary particle front too. Not only have new particles been discovered but antiparticles as well whose principal characteristic is a sort of death wish. On contact with its particle an antiparticle, and the particle, are annihilated in a flash of light—a principle which some of my colleagues are using to examine the properties of the anti-electron.

In order to indicate the complexity of the present situation I list in Table I some of the particles which

TABLE I.

Particle	Symbol	Electric Charge	Rest Mass (MeV)	Velocity*	Agent of	Strength
Graviton ?	g	0	0	c	Gravitational force	1
Neutrinos †	$\nu_e, \bar{\nu}_e$ $\nu_\mu, \bar{\nu}_\mu$	0	~0	c		
Photon	γ	0	0	c	Electromagnetic force	10^{38}
Tachyon ?	t^+, t^-	± 1 ?	imaginary	>c		
Electron	$e, \bar{e}$	± 1	0.51	<c		
Mesons	μ^+, μ^- π^o, π^+, π^- K^o, K^+, K^- and their antiparticles	± 1 $0, \pm 1$ $0, \pm 1$	105 140 498	<c	Strong force	10^{40}
Heavy Leptons ?	-	$0, \pm 1$	~430	<c		
Proton	$p, \bar{p}$	± 1	938	<c		
Neutron	$n, \bar{n}$	0	939	<c		
Intermediate Boson ?	W	0	> 20,000	<c	Weak force	10^5
Quarks ?	$q^+, q^-, \bar{q}^+, \bar{q}^-$	$+\frac{1}{3}, +\frac{2}{3}$	> 4,500	<c		
Strange particles (omega minus, etc.)		(Compounds of neutrons, protons and mesons)		<c		

* c = velocity of light.

† The bar above a symbol indicates an antiparticle.

physicists have either already discovered or now believe could exist.

This plethora of particles might be considered daunting. We can see that what started out as a simple scheme of two particles and two force fields has become progressively more complicated and has now turned into an avalanche of new concepts, new particles and new fields. Nevertheless an ordered scheme prevails. Admittedly it is one with big gaps in it and with several inconsistencies to be removed and too, conflicts to be resolved. But there is symmetry. Indeed it was the development in the late-50's and mid-60's by theoreticians like Dyson, Feynman, Schwinger, Gell-Mann and Ne'eman of quantum-field theory and of the algebras of symmetry that cast so much light on the behaviour of the known particles and led to the prediction of the existence of some of these particles, such as the omega-minus, before the experimentalists discovered them. The symmetry principles are well established, but the detailed nature of many of the particles and how they interact, through weak and strong forces, is by far from clear. There is a very exciting challenge here.

Of the particles listed the neutrino turns out to be the most common in nature. There are more of them than there are atoms in the universe and their total energy is much more than that of all the visible stars. About 10^{16} neutrinos pass harmlessly through this room every second. Yet we are not aware of them since the neutrino possesses no mass, carries no charge, moves with the velocity of light and is practically unstoppable—a veritable Gareth Edwards of the sub-nuclear world! Although their existence was predicted in 1930 by the Swiss physicist Pauli in order to preserve the laws of conservation of energy and momentum they were not detected until 1956, and then only in their antiform. But a distinguished former student of this Department, the late Professor E. J. Williams, came within an ace of finding them in Aberystwyth in 1938. He had built a novel type of cloud chamber for cosmic ray studies and with this he was the

first to detect the actual decay of a meson into an electron. We now know that this decay is always accompanied by a neutrino, but his apparatus, which cost only a few pounds to make, was not sufficiently sensitive to detect this most elusive of all known particles.

Another intriguing entity is the tachyon, a particle which always travels with velocities greater than that of light. Tachyons have, as yet, not been detected experimentally. Yet there is nothing in relativity theory which precludes their existence, provided that they have an imaginary rest mass.

Of the others in the list the quarks are perhaps the most exciting and yet disturbing. They are expected to be very massive and, most awkwardly, to carry an electric charge which is either only one-third, or two-thirds of what we have come to regard during the last seventy years as the irreducible electronic charge! Three of them together may constitute the internal structure of a proton. The great quark hunt is now on.

These advances in our knowledge of the physical world and the measure of control that they have given us over many of nature's processes now stand as part of the fabric of our society and will to a large extent determine its future course. For there is no doubt that society is becoming increasingly dependent upon science and that society is growing more aware and perhaps a little more apprehensive of this dependence. It is not surprising then that science, like the other establishments, is under attack from many quarters. A great deal of the basis for the attack is illogical and sometimes based on the failure to recognize that the physical principles underlying a sword and ploughshare are the same. Scientists themselves must accept a portion of the blame for not having taken more opportunities of explaining and justifying their activities to society in a language understandable to the non-specialist. Perhaps it is a dislike of a too pragmatic attitude to his work that has inhibited the physicist in meeting this particular obligation more fully. In partial answer one can point to the benefits which have accrued from his work over the years. For example, to the growth of electronics and communications and their application throughout commerce and industry ; these have origins in atomic and ionization physics : to the advances in medicine which stem from the applications of atomic and nuclear radiations in diagnostic and therapeutic rôles : to the progress in computers which owe their very existence to solid state physics, and turning to the future, we know that energy supplies will not come from fossil fuels, which will be exhausted within the next hundred years, but from nuclear fission and probably fusion.

These are but some of the contributions to society stemming from researches carried out by physicists over long periods. It is appropriate to point out that they arise from applications of but three of the particles in Table I—the electron, the proton and the neutron. It would be a brave man who would state that the others will not, in the fulness of time, play equally important roles for society. It should be remembered that the research physicists' work is often of a long term nature and I would like to reaffirm the view that it is wrong of society to expect immediate returns on all its investment in physics.

Of course, not all physicists are researchers. By far the greater number of them are engaged in an enormous variety of activities in private industry, government and public services, education and so on where returns are in the short term if not immediate. This range of activities reflects physics as an excellent form of training which inculcates the practical, logical and numerate attitude, and which instils the habit of sustained hard work without eroding the powers of fanciful thought, though the latter must be quantitative ! It is frequently just these attributes which enable physicists successfully to fill widely diverse posts outside physics. It is their flexibility of mind which often appeals to employers and the signs are that in these difficult times physicists are faring rather better than graduates of many other disciplines.

II. Physicists

One may well ask what manner of men and women are these who, in their continuing search for understanding, have had so often to reject what had become established fact and to accept *volte-face* of their ideas and face *double-entendre* in Nature's behaviour, with equanimity ?

There seem to be, broadly speaking, two images which the general public has of them. One, held curiously enough by the younger generation, portrays the physicist in a saintly light. More often than not they imagine him as elderly or middle-aged, stooping and tired, but always dedicated, stubbornly optimistic, intelligent and patient. A paragon of virtue on whose shoulders the future rests and whose inventions will make life easier for everyone. The other view is perhaps best summarized by the cartoon which appeared in the New Yorker some years ago, with the caption "Now, don't be so modest Professor, I'm sure you've got something up your sleeve that will blow us all to bits".

Anthropological surveys (3) suggest that, like other scientists, the physicist is characterized by a need for independence, for autonomy, for mastery of the environment. He is attracted by facts which seem to be mutually contradictory and finds it challenging to reconcile them. In his attitude towards his work he tends to be rather self-sacrificing; holidays, for example, are often regarded as annoying interruptions—a fact to which many wives present can testify. He tends to be open-minded about religion and somewhat careless about church-going.

The research physicist has a strong ego which sometimes makes him over-dignified and likely to keep an unduly tight rein on himself. He is not usually impulsive or talkative. Emotionally he is both sensitive and stable. Though often inclined to be highly critical of others, he avoids personal controversies. When embarrassed socially he tends to move away from the offender and represses any outward show of hostility. He does not brood but immerses himself in his work. This preoccupation with physics might account for the fact that his marriage is likely to be eight times less probable of ending in divorce than is that of a social scientist!

Perhaps the best summary of their characteristics has been provided by another distinguished former student of this Department who made major contributions to the development of radar and is now one of Australia's leading scientists—Dr. E. J. Bowen. He states that "They are just like everybody else. They all have their failings. Some are dedicated, some unscrupulous, some sharp as a whip, others dull as ditchwater. I've known some of the great names of science, men who have done tremendous good for the world. And while I've not known one who's been in jail, I've known some who richly deserved to be": but, to be fair, I think he was talking about scientists in general. In other words, physicists, like all scientists, are human beings. This is an established experimental fact.

III. Light

For many years my abiding passion has been the study of the behaviour of electrons, ions and photons in gases, though I must confess to some mild flirtations with mesons, neutrons and neutrinos. My interest in electrons goes back a long way, to my schooldays at Ammanford where I was puzzled by the fact that although I knew electricity was conducted through gases by the motion of electrons and ions I could not understand where the first free electron which started the conduction process came from. To my astonishment neither did John Andrew Owen, one of the finest physics teachers one could have wished for. Of course one does not have time to pursue these interests when doing A-levels and so the matter dropped until it was revived tepidly by some observations I had made during national service on the curious behaviour of high frequency radiation in wave-guides. My interest was sharpened when I returned to College after the war. It was then, in the course of lectures on

gaseous electrical conductors, a subject of vital importance in electrical engineering, given by Mr. R. G. Isaacs, the acting head of the Engineering Department, that the question of the origin of the first free electron again arose in an acute form. By now my curiosity was thoroughly aroused. The aim was strictly practical. If one could discover their origin and suppress them many serious electrical breakdown problems in industry could be overcome. Better still, if one could control their appearance, many interesting possibilities in current switching would arise. In assuaging this burning desire for knowledge I realized that a fundamental approach was required and this led me to the Physics Department Library. In those days, a quarter of a century ago, the library was a shelf in the office adjacent to the Professor's room and so, quite fortuitously, since the timing of my visit coincided with the end of one of his lectures, I met and spoke to the Professor for the first time. I will not dwell upon this chance meeting with the man who is now our Principal except to say that it exerted a profound influence on me. Yes, the origin of the first electron was important! What was more it was already under intensive study here in the Physics Department and considerable progress had already been made. Its ramifications were even wider than I had ever imagined. Brimming full of the enthusiasm which he so successfully inspires, I made up my mind (or was it made up for me ?) to take up physics in earnest. It has been said, not unkindly, that it was then that I began to see the light. It is appropriate for me, at this juncture, to acknowledge my great personal debt to Principal Frank Llewellyn-Jones, the man who opened my eyes and who set me on what is a most enjoyable and stimulating way of life.

One of the main research interests of this Department at present is the interaction of radiation with matter. This is not a new subject to Swansea physicists. I have already mentioned Professor E. J. Evans' major contributions of sixty years ago. Professor P. M. Davidson also made distinguished contributions in this field, beginning with his work on the quantum theory of the hydrogen molecule in the early thirties, and continuing right up to his untimely death two years ago. The Principal has made important advances on this topic in his studies of the rôle of various radiations in the growth and maintenance of electrical discharges and in their application to spectral analysis. I am therefore following a traditional Swansea preoccupation. The particular form that it takes has been a possibility only during the last seven years since the invention of the Q-switched laser. A laser is a rather special type of lamp which produces highly distinctive light. The distinctions lie in the purity of its colour, in the coherence and directionality of the light beam and in the extraordinarily high intensities which can be reached, surpassing those from any other type of lamp by many orders of magnitude.

Lasers (the name is derived from the initial letters of the phrase **L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation) are the practical realization of a theory of how light and atoms interact, developed by Einstein in 1917. You will recall that I said earlier that light arises from atoms when their electronic orbits are perturbed. In an ordinary lamp, be it a candle, a hot filament in a bulb, or a glowing gas in a fluorescent tube, the orbits of the electrons in millions upon millions of atoms are perturbed by the energy supplied by the combustion of gas in the flame, or by the passage of electric current through the filament or tube. The electrons in the atoms gain energy and then spontaneously and in an entirely random manner give up this energy as light quanta. There is no correlation between the time a quantum is emitted from one atom and the time a quantum is emitted from another. There is certainly no preferred direction of emission. The light comes out at all times and in all directions. It is said to be temporally and spatially incoherent. This is a basic characteristic of ordinary lamplight. In lasers the situation is entirely different. There is a very high degree of coherence and directionality. It comes about as follows. By carefully selecting suitable atoms and supplying them

with energy they become agitated and their electrons acquire a state known as excitation—an over-abundance of energy. Now, when an excited atom is acted upon by a light quantum which has an amount of energy exactly equal to that of the excited atom (within the limits allowed by the Uncertainty Principle) the electron is forced down to its normal unexcited state and instantly gives up its excess energy in the form of a light quantum identical to the first. That is, the atom is stimulated to emit radiation. So we now have two identical quanta. What is equally important, the second quantum moves in step with the first and in the same direction. This process can be repeated. Thus if one of these two quanta encounters another appropriately excited atom, a third quantum of light is produced, which keeps in pace with the other two—and so on, and so on. An avalanche of light builds up which has temporal and spatial coherence to a very high degree. The secret lies in the careful choice of atoms so that they have just the right electronic configuration and in producing enough of them in the correct excited state. It is essential to have very many more in this excited state than in the normal unexcited condition. This is an entirely unnatural situation, referred to as a population inversion or negative temperature. By placing all of them between parallel mirrors it only requires one spontaneously emitted quantum to travel along the line orthogonal to the mirrors to start up the process of stimulated emission from all the remaining excited atoms so that the coherent quanta, passing to and fro from one reflecting surface to the other will build up in intensity and quickly form a beam of quite extraordinary spectral purity. By making one of the mirrors slightly transparent a portion of the beam will emerge to serve our purpose.

The first successful laser operation was achieved in 1960 by Maiman following the development of the maser, a microwave amplifier, by Gordon, Zeiger and Townes in 1954. Since then there has been an enormous increase in the variety of lasers which now cover wavelengths from

U.V.-rays to the far infra-red, over an equally impressiev scale of power. They have lead to advances in practically all branches of science, medicine and technology.

Some of the differences between ordinary lamplight and laser light become immediately obvious from just one brief glance at a laser beam falling on a surface. Firstly its brightness is far greater than that of ordinary light even though the power may be only one thousandth of a watt. Secondly, the way it stays as a narrow beam without significant spread even though it is projected over long distances, and thirdly, its distracting sparkling appearance. This is due to the property of spatial coherence which I mentioned earlier coupled with the fact that one cannot keep one's head still to better than half a wavelength of light. As we move unintentionally, and ever so slightly, the lengths of the light paths from the various parts of the spot to our eyes change and so we see a continually changing interference pattern as the light waves add or subtract in intensity when they reach the retina. The light, produced by quantum effects, here shows its wave character.

A laser beam has an amazing propensity for carrying and storing information. This is because the rate at which information can be transmitted depends upon the frequency, or, more precisely, upon the frequency bandwidth of the beam. In the case of a laser this is more than ten thousand times greater than for radio waves. In principle then it is possible for just one laser beam to carry all the information now being transmitted by all the telephone, radio and television networks in this country.

An example of the use of the coherence properties and strong light intensities available from lasers is the hologram. This is a photographic record of the interference pattern of laser light scattered by an object when the light is allowed to fall directly onto it and also by another indirect route. In this way the light recorded on a film contains all the information about the object, although, to look at in ordinary light it is merely a series of points bearing no resemblance to the object

photographed. However, when looked at in laser light all the information is reconstructed—even down to the 3-D effect.

The retention of all information and the fact that it is possible to focus laser light down to very small spot sizes makes possible the storage of up to one hundred thousand bits of information in a few square millimetres of film. Arrays of such holograms then offer exciting possibilities as computer memories with very high access rates.

It is nowadays a relatively simple matter to produce a flash of laser light having a power of hundreds of millions of watts. When focused such a flash may have an intensity of millions of millions of watts per square centimetre. The result can be quite dramatic. For example, ordinary air, normally an excellent insulator of electricity can be turned into a perfect conductor in a time as short as a few thousandths of a millionth of a second, and transformed into a glowing globule of plasma at a temperature of a few million degrees—much hotter than the sun.

It is this ability of laser light to produce intensely hot dense plasmas that has brought forward the prospect of the controlled release of thermonuclear energy by the fusion of light nuclei to a point in time which is rather closer than seemed possible a year or two ago. The achievement of a practical fusion reactor would have a most profound effect upon all aspects of society. It would represent a virtually limitless source of electricity free from the potential hazards of radioactivity which arise in fission reactors and without the pollution caused by burning fossils fuels.

We have found that the process of plasma production is rendered much easier by the use of long wavelength light. We now know that the intensity required depends inversely upon the square of the wavelength so that far infra-red radiation such as that from a carbon-dioxide laser is about two-hundred and fifty times as effective as the red light from a ruby laser. This fact underlies one of our present researches into an entirely new type of high energy nuclear particle detector based on plasma production along the tracks of elementary particles passing through a gas. If we succeed in perfecting the system we will be able to join in the quark hunt at minimal expense. We can look for them in cosmic rays which are free.

Focused laser light is not without its problems. Its purity of colour renders it highly subject to the interference phenomena which I mentioned earlier, and when the light rays are brought to a focus the possibilities of interference greatly increase. So much so in fact that a multiplicity of foci arise. We discovered this phenomenon in a rather indirect way when I was concerned with improving methods of producing beams of pure K-mesons from the CERN proton-synchrotron in Geneva in 1965. It proved helpful then to use a very powerful ruby laser beam for this purpose and, during the progress of the work we noticed that the focussed beam produced two, three or even four sparks in air near the region where only one was expected. This multiplicity is illustrated in figure (1).

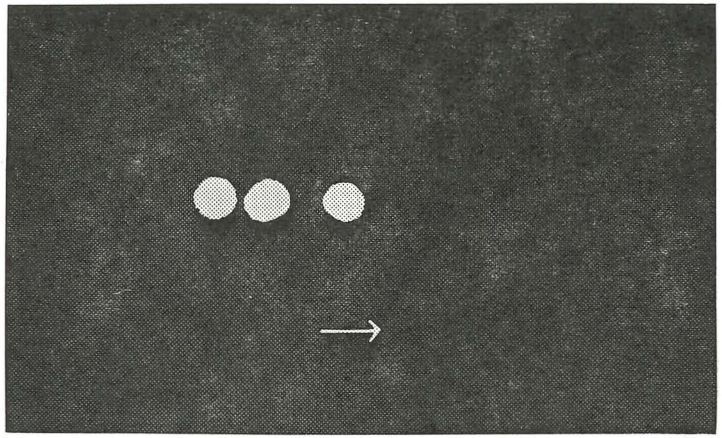

Figure (1)

Three plasmas produced in air by a single flash of laser light ; magnification x50. (Arrow represents beam direction).

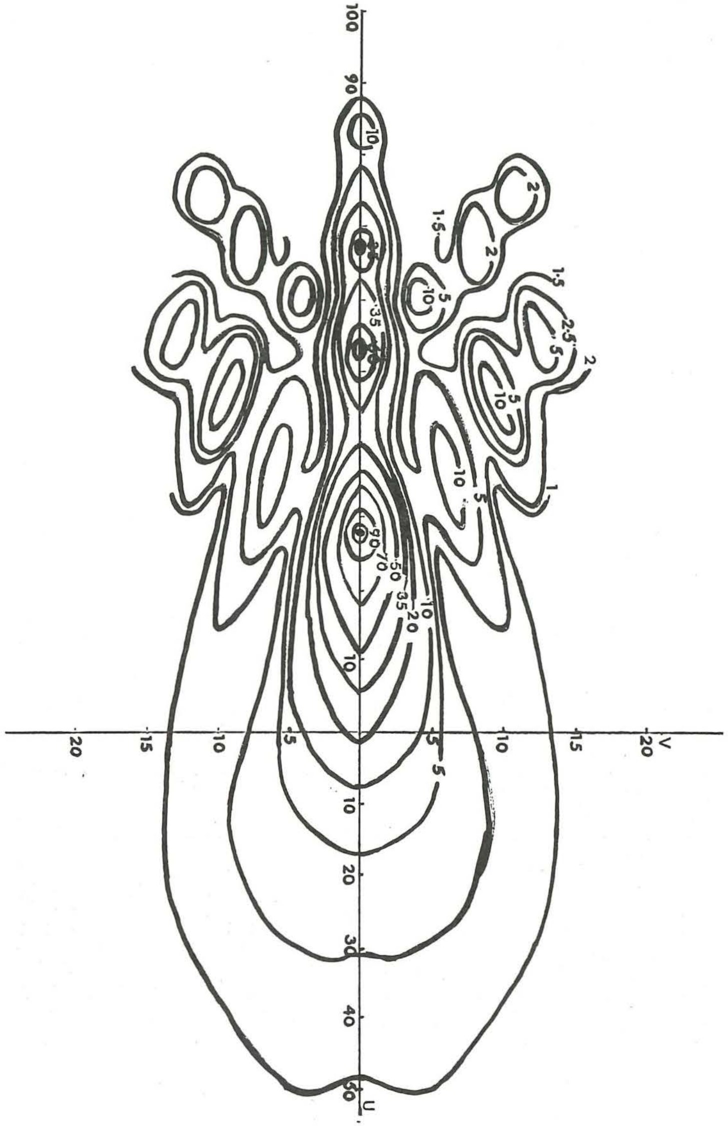

Figure (2)

Lines of constant light intensity in the focal region of a system having six wavelengths of spherical aberration. Beam direction is from top to bottom.

The explanation lies in the complex distribution of the light intensity caused by the interference, the extent of which depends upon the focusing lens and beam size. How complex this is can be seen in figure (2), which shows our computed isophotes—lines drawn through points of instantaneously constant light intensity—rather like a geographer's contour map of lines of constant height above sea level. The foci are where the lines are most concentrated and in this example there are no fewer than three sharp peaks of intensity lying along the axis and extending over distances of millimetres. At each peak it is possible for a plasma to be produced.

Unknown to us, and at about the same time, astrophysicists at the Arecibo Observatory in Puerto Rico were encountering similar interference problems in the focusing system of their radio telescope which was being used to probe the planets and outer space. But, since they were focusing relatively long wavelength radio waves by means of a very large telescope, the separation between foci was very much larger—amounting to as much as fifty feet. This required the construction of a small railway to transport the radio wave detecting apparatus to the most intense region. When scaled down, I am glad to say that their results and ours agree well. It is an interesting illustration of the enormous range of application of electromagnetic theory.

These results have serious implications for the use of focused laser beams in medicine and biology where, as you all know, laser beams are finding increasing application not only as therapeutic devices but also as an essential part of the equipment used in a variety of medical, dental and biological studies. Their use in the treatment of retinal tears and for arresting progressive blindness caused by diabetes is now well established. In biological investigations advantage may be taken of the very large local electric fields, some tens of millions of volts per centimetre, created by focused beams to produce large voltages across transparent biological specimens, nerve synapses, and so on. By this means

electrical effects can be separated from thermal effects. It has provided the geneticist with the means of selectively changing parts of individual cells. In all these applications a well defined beam is essential and our work has shown how important it is to take into account the interference characteristics of the focusing lens and the special nature of laser light.

These considerations may be regarded as a spin-off from our main researches. There have been others, such as a simple and inexpensive method for accurately controlling and measuring the intensity of polarized laser beams. The device, shown in figure (3), allows one to change the beam intensity over a wide range merely by turning a knob. It replaces other much more expensive and unreliable methods which could not be used successfully at large powers.

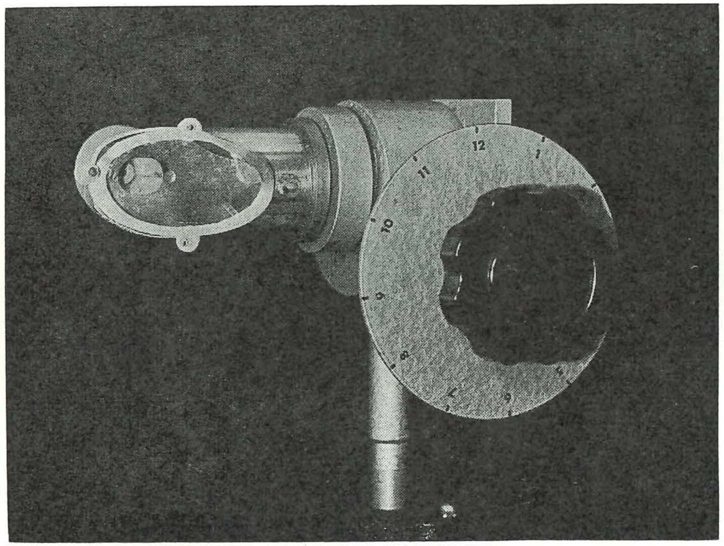

Figure (3)

Laser beam power control device constructed by Mr. F. B. Homeyard

I have mentioned only a few of the applications of laser light. It is tempting to add to this list and cite examples of the rôle that laser light is playing in other fields such as chemistry, engineering, geology and so on; but, bearing in mind the hazards of hyperbole, I must bring it to a close.

In this talk I have tried to shed some light on physics as I see it, conscious of the fact that it is but a limited view of some few aspects of a discipline with ever-widening frontiers and more and more demanding challenges. It is these which make it so attractive.

It seems to me that we are now in the earliest stages of a quiet revolution, rather like the ones ushered in with the discoveries of the electron and the neutron. This time it is the photons that make up light which are going to play an increasingly important rôle in our affairs. We can hope that for this, and other reasons, future historians may look back upon this time and describe it as the dawning of the age of light.

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