Matter and Radiation.*

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THE title of this lecture might suggest a discussion of the greater part of physical and chemical science. It is proposed, however, to confine the following remarks to a consideration of certain views and theories concerning the reciprocal inter-conversion of matter and radiant energy.

Some twenty-five years ago Jeans proposed, as an explanation of the enormous energy radiated by the stars, the startling hypothesis that matter might, under certain conditions, suffer a process of 'annihilation', whereby a proton and an electron might coalesce, and, disappearing as matter in the ordinary sense of the word, be converted into energy of radiation. The basis of Jeans's hypothesis was given by the special relativity theory of Einstein, which showed that matter and energy can be mutually related. Thus the energy corresponding to a mass m grams of matter was found by Einstein to be equal to mc^2 ergs, where c is the velocity of light in centimetres per second. Similarly, if E be the energy in ergs of a given quantity of radiation, its mass in grams is given by the expression E/c^2. We may express Jeans's idea by means of the equation $P+E=$Radiation, where $P=$proton and $E=$electron. Now the mass of $P+E$ is equal to the mass of a hydrogen atom, and this is equal to the reciprocal of the Avogadro number N, the value of which is known to be $6{\cdot}06\times10^{23}$. Hence it is possible to calculate the energy of the radiation produced in the above reaction.

The development by Einstein of Planck's quantum theory enabled Jeans to carry this calculation one step further. If we suppose that the coalescence of P and E produces one quantum of monochromatic radiation (one 'photon'), we know that the energy of this quantum is given by the expression $h\nu$ where h is Planck's constant of action and ν the frequency of the monochromatic radiation. We can now write Jeans's hypothesis in the form of an equation, namely, $mc^2=h\nu$, and this equation enables us to calculate the value of ν, since

$$m=\frac{1}{6{\cdot}06\times10^{23}},\quad c=3\times10^{10},\quad \text{and}\quad h=6{\cdot}5\times10^{-27}.$$

This calculation gives as a result $\nu=2{\cdot}2\times10^{23}$, the corresponding wave-length being $\lambda=1{\cdot}3\times10^{-13}$ cm.

Twenty-five years ago no radiation of this high frequency was known to science. Recent investigations on the so-called cosmic rays, which reach us from all parts of the heavens, have shown, however, that this radiant energy of cosmic origin contains frequencies equal to and greater than the frequency calculated above. Such results indicate, therefore, that some such hypothesis as that of Jeans is very probable, and that in the depths of space phenomena are occurring which are capable of producing photons of extremely high frequencies.

In the subsequent development of his theory of stellar radiation, Jeans has propounded the interesting hypothesis that in the interior of stars and nebulæ there exist very large and complex atoms which are much more massive than any known to us in the earth. In these 'super-radioactive' atoms Jeans supposes that electrons circulating near the atomic nuclei occasionally fall into the nuclei and, combining with the protons, produce the energy of stellar radiation as a resultant of the 'annihilation' of matter, that is, of electrons and protons. These actions are regarded by Jeans as independent of temperature and characteristic of the complexity and instability of the massive atoms. I do not intend to follow here the later hypothesis of Jeans, and propose to deal with the reaction $P+E=$Radiation as a *chemical* reaction occurring between *free* electrons and protons. This reaction, if it be possible, is certainly the simplest and most fundamental of all chemical reactions and therefore worthy of the closest study.

We may observe two things about such a reaction. It evidently does not occur under any except very unusual conditions, as otherwise the material universe could not endure for very long. We may suppose that some very intense source of 'activation' is necessary, such as an extremely high temperature or possibly very high velocities of collision due to extremely high electric fields. The reaction is a very strongly exothermic one, so that the reverse reaction would be likely to occur only at excessively high temperatures. Given a system consisting of free protons and electrons, a proton-electron 'gas', we may therefore imagine the reversible equilibrium

$$P+E \rightleftarrows \text{Radiation}$$

as occurring in a closed space at a given temperature, and endeavour to obtain some idea of the temperatures which would be necessary. Only photons of frequency equal to or greater than $2{\cdot}2\times10^{23}$ could transform into a proton-electron pair. If the temperature were such that the *hohlraum* radiation were rich in frequencies of this high order, we might expect the possibility of such an equilibrium, assuming that this temperature was high enough to 'activate' the forward reaction. Given such assumptions, there are two very simple ways of calculating a possible temperature. The well-known formula $\lambda_m T=0{\cdot}3$ gives the wave-length λ_m of the radiant energy of maximum density in a closed space at a temperature of T degrees on the Kelvin thermodynamic scale. The frequency ν corresponding to λ_m being given by the equation $c=\nu\lambda_m$, we obtain the result $T=\frac{0{\cdot}3\,\nu}{c}$. If we now identify ν with $2{\cdot}2\times10^{23}$, it follows that

$$T=\frac{0{\cdot}3\times2{\cdot}2\times10^{23}}{3\times10^{10}}=2{\cdot}2\times10^{12}\ {}^\circ\text{K}.$$

Thus in a closed space at a temperature of the order of 10^{12} K, that is, one billion degrees, it would be

* Digest of a lecture delivered to the Research Department of the Metropolitan Vickers Electrical Company on June 12.

possible for the reversible equilibrium $P+E\rightleftarrows$ Radiation to exist. Under these conditions matter, in the form of protons and electrons, would be constantly dissolving into radiant energy, and simultaneously radiant energy would be constantly giving birth to protons and electrons.

Another approximate way of calculating the necessary high temperature is the following. We start with the well-known equation for the variation with the temperature of the equilibrium constant K of an ideal gas reaction, namely, $\frac{d\log K}{dT}=\frac{Q}{RT^2}$ where Q is the heat of the reaction. If Q does not vary with temperature, the integrated form of this equation is $\log K=\frac{-Q}{RT}+\text{constant}$, which we may write in the form $K=k_1e^{-Q/RT}$, where k_1 is another constant. In this form of the equation, Q and R refer to gram molecules. If we divide both these quantities by the Avogadro number N (that is, the number of molecules in a gram molecule) we can state the equation in a form referred to molecular magnitudes: $K=k_1e^{-q/kT}$, where $q=Q/N$ and $k=R/N$ (called the Boltzmann constant).

Now if q is an extremely large quantity, it is necessary that T should have a very great value if K is to possess an appreciable magnitude. We observe, for example, that $K=k_1/e$ if $q=kT$. Now although it is not possible in the present case to define the equilibrium constant K in the usual way, let us, nevertheless, apply the foregoing reasoning, and write therefore $q=mc^2=kT$, or $T=mc^2/k$. Since $m=1/N$ and $k=R/N$, this gives the result $T=c^2/R$. Recollecting that $c^2=9\times10^{20}$ and $R=8{\cdot}4\times10^8$ ergs, we get $T=10^{12}$ °K, which is approximately the same result as before.

We might have used the Planck radiation equation in these approximate calculations. We shall employ it now, however, for a somewhat different purpose. This equation gives the distribution of radiant energy E as a function of the wave-length, and we may write it for our present purpose in the form:

$$E_\nu=\text{const.}\frac{\nu^2}{e^{h\nu/kT}-1}.$$

In the present case

$$\frac{h\nu}{kT}=\frac{mc^2}{kT}=\frac{c^2}{RT}=\frac{10^{12}}{T},$$

so that we have

$$E_\nu=\frac{\nu^2}{e^{10^{12}/T}-1}.$$

For two different temperatures T_1 and T_2 and the same ν

$$\frac{(E_\nu)_{T_1}}{(E_\nu)_{T_2}}=\frac{e^{10^{12}/T_2}-1}{e^{10^{12}/T_1}-1}.$$

If we put $T_2=10^{12}$, $T_1=10^{10}$, we get

$$\frac{(E_\nu)_{T=10^{10}}}{(E_\nu)_{T=10^{12}}}=\frac{e-1}{e^{100}-1}=\frac{1{\cdot}7}{e^{100}}.$$

Hence, in comparison with the energy density of radiation of frequency $\nu=2{\cdot}2\times10^{23}$ at $T=10^{12}$, the energy density of this radiation at $T=10^{10}$ will be negligibly small. It follows, therefore, that the reverse reaction Radiation $\rightarrow P+E$ would be practically non-existent at $T=10^{10}$, though very marked at $T=10^{12}$. Thus if the temperature 10^{10} were high enough to activate strongly the forward reaction $P+E\rightarrow$ Radiation, matter (in the form of protons and electrons) would dissolve into radiation practically completely.

Quite recently, E. A. Milne has given an important theoretical treatment of the reversible thermodynamic equilibrium $P+E\rightleftarrows$ Radiation, employing for this purpose the quantum statistics of Fermi and Dirac. If n is the number of protons, or the equivalent number of electrons, present per cubic centimetre at statistical equilibrium, then Milne's result may be expressed in the form:

$$n=\frac{2^{\frac{1}{2}}}{h^3}[2\pi kT(m_e/m_p)^{\frac{1}{2}}]^{\frac{3}{2}}e^{-\frac{1}{2}\frac{mc^2}{kT}}$$

where $h=$ Planck constant, $k=$ Boltzmann constant, $m_e=$ mass of one electron, $m_p=$ mass of one proton, $m=m_e+m_p$. Employing the known values of the constants and changing to 10 as exponent base, Milne's equation reduces to:

$$n=0{\cdot}96\times10^{18}T^{\frac{3}{2}}\times10^{-\frac{2\cdot35\times10^{12}}{T}}.$$

The following short table gives a few of the results calculated by Milne by means of this equation.

T	n (No. of Protons per c.c.)	ρ_m (Grams per c.c.)	ρ_R (Grams per c.c.)
10^{10}	10^{-202}	$1{\cdot}65\times10^{-226}$	$0{\cdot}85\times10^5$
10^{11}	10^{11}	$1{\cdot}65\times10^{-13}$	$0{\cdot}85\times10^9$
10^{12}	10^{65}	$1{\cdot}34\times10^{10}$	$0{\cdot}85\times10^{13}$

In this table, $\rho_m=$ density of matter and $\rho_R=$ density of radiant energy. ρ_R is calculated from the equation $\rho_R=\frac{aT^4}{c^2}$, where $a=$ Stefan's constant.

It will be seen that our former rough calculations are in qualitative agreement with Milne's results. Imagine hydrogen gas gradually heated up in an enclosed space. Then we have the following picture. As the temperature rises the molecules will be ionised and finally completely dissociated into atoms. With sufficient further rise of temperature the atoms will become ionised, and when this process is practically complete we shall have our proton-electron gas. We must now imagine that at some very high temperature the reaction $P+E\rightarrow$ Radiation sets in. Milne's results show that at $T=10^{10}$ this reaction will be practically complete. As the temperature rises still higher the reverse reaction, the 'birth' of matter from radiation, begins to be appreciable, and we see that at $T=10^{12}$ the equilibrium density of matter becomes equal to $1{\cdot}34\times10^{10}$ grams per c.c. The state of affairs at $T=10^{12}$ corresponds in fact to enormous densities for both matter and radiation.

We can never expect in our laboratories to attain to temperatures of this order of magnitude. Our only hope in this matter, as in so many other related problems of physico-chemical science, lies in the technical progress of electrical science. Only through the attainment and control of enormous voltages are we likely to obtain results equivalent to the very high temperatures discussed previously. Let us calculate, for example, the energy value of mc^2 in terms of electron-volts. We must write (where V = voltage and e = electron charge)

$$eV = mc^2 = \frac{c^2}{N} = \frac{9 \times 10^{20}}{6 \times 10^{23}} = 1{\cdot}5 \times 10^{-3}.$$

Now $e = 4{\cdot}8 \times 10^{-10}$ e.s.u. Hence $V = 0{\cdot}3 \times 10^7$ e.s.u. Since one electrostatic unit of voltage equals 300 volts, $V = 300 \times 0{\cdot}3 \times 10^7 = 9 \times 10^8$ or nine hundred million volts.

It does not follow, of course, that voltages of this enormous value would be necessary, since we only require electrical potential gradients sufficient to impart to protons and electrons the energies required for 'activation', that is, the energies required to overcome the repulsive forces which exist at very small distances. We might say, at a guess, that controllable voltages of the order of a hundred million volts would be likely to initiate an entirely new era in physico-chemical science. The future progress of this fundamental science lies, therefore, in the hands of the scientific electrical engineer. It is to be earnestly hoped that these advances will be made in England, the land where the electron and proton were discovered by Thomson and Rutherford, and the land where one hundred years ago Faraday discovered how to set electrons in ordered motion by moving magnetic fields.

If we turn back now to our enclosure in chemical and radiant equilibrium at a temperature of 10^{12} degrees, we know that there exists in such an enclosure a sufficient density of photons of frequencies equal to $2{\cdot}2 \times 10^{23}$ and upwards, that is, of photons which can transform into proton-electron pairs. Suppose that from such an enclosure there could escape a dense stream of radiant energy of frequencies lying between, say, $2{\cdot}2 \times 10^{23}$ and 10^{24}. Imagine a sufficiently dense stream of this type of radiation to escape into *cold* interstellar space, and perhaps there to encounter another similar stream. What might happen? Is it not extremely probable that matter would be generated? The reverse reaction radiant energy $\rightarrow P + E$ does not *necessarily* demand a very high temperature. It would be enough if there existed a sufficient density of photons of frequency equal to or greater than $2{\cdot}2 \times 10^{23}$. Such a reaction would be, indeed, the most fundamental synthetic photochemical reaction. Now photons of such frequencies are known to be reaching our planet from all directions in space. It seems quite possible, therefore, that matter may be in process of generation in cold interstellar space, whereas temperatures such as 10^{12} could only be expected to occur in the hot cores of stars, as Milne has suggested.

Jeans and Eddington tend to emphasise the 'running-down' of the universe, the steady dissolution of matter into radiation. It seems likely, however, that, although the total effect may be such a running-down, there exist places in the universe where a 'running-up' may occur, even though this running-up be of a temporary nature. The universe is probably in a state of fluctuation. It is certainly large enough to permit very considerable local fluctuations, and such fluctuations are by no means incompatible with that general running-down process which the second law of thermodynamics seems to demand. It may be true that the universe, as a whole, is passing from a less probable to a more probable state, from a state of greater to a state of lesser organisation. This general drift, however, is quite compatible with intense local fluctuations in the opposite direction. The re-conversion of radiation into matter may be one of these.

Southern Whaling.*

IN "Southern Whaling" Sir Sidney Harmer reviews the present position of the whaling industry and summarises our knowledge, obtained largely as the result of commercial operations, of the biology of the great whales. The statistics, gathered with scrupulous care, show clearly the great concentration of modern commercial operations in the southern hemisphere, where on the average three-quarters of the annual world-catch of whales is obtained. Since hunting began in that region at the beginning of the present century, quite half of the world's catch has been made in the Antarctic, while African waters have contributed another quarter. Modern whaling operations, therefore, are conducted principally round the great ice barrier which surrounds the south pole.

Analysis of the species captured by the commercial vessels shows the great preponderance of finner whales in the catches, 90 per cent of which consists of the four species—Blue, Fin, Humpback, and Sei. Of these, the Blue and the Fin contribute on the average three-quarters of the total captures, so that the industry is largely dependent on the available stock of these two species. The annual world-catch of all species of whales has risen from 11,000 in 1919 to about 30,000 in 1929 and is still increasing, and the percentage of Antarctic Blue and Fin whales in the total world-catch has risen correspondingly from 63 to 85.

Recent researches into the life-histories of Blue and Fin whales have established that the period of gestation of these species is about a year, and that the young are born at the most every alternate year. Propagation, therefore, is slow. It has been noted that the percentage of sexually mature females in the catches is decreasing, while evidence has also been brought forward which points to a steady decline in the average length of whales captured in Antarctic waters in recent times. In connexion with the latter feature, it is to be remembered that, in whale hunting, the larger

* "Southern Whaling." By Sir Sidney Harmer. *Proceedings of the Linnean Society of London*, Session 142, 1929–30.