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AVAILABLE ENERGY[1]

ASTRONOMY is often called the most useless of the sciences, and so it is from the standpoint of the man whose time-horizon extends ten years forward and ten years backward; and that man, too, probably represents ninety per cent. of all mankind. But for the smaller fraction of men who have been able to rise above the mole's outlook, who have studied enough of the past and understood enough of the present to have acquired a three hundred year time-horizon, for all such the foregoing statement is grotesquely incorrect.

If utility consists in nothing more than feeding and clothing the generation now living, then there are indeed *useless* sciences, and astronomy is perhaps one of them. But again, if utility consists in nothing more than feeding and clothing ten successive generations, then, even by that narrow standard, the verdict of history has definitely been that astronomy is one of the most useful of all the sciences, more useful probably than physics, chemistry, geology or engineering, and that for the simple reason that without it there would presumably never have been any modern physics, chemistry, geology or engineering. Eliminate it and you probably eliminate with it the development of the whole of Galilean and Newtonian mechanics: you certainly eliminate the discovery of the law of gravity, and of all the principles of *celestial* mechanics, and you probably eliminate even the discovery of the laws of force and motion. All these discoveries which came out of the labor and travail of two long centuries, the seventeenth and the eighteenth, which had to create even a new mathematics in order to be able to handle the new group of physical ideas, constituted an indispensable foundation for the crowning achievement of the nineteenth century, namely, the *application of these same laws to the development of terrestrial mechanics,* an achievement out of which has grown most, if not all, of the *distinctive* features of *modern* civilization.

Utility can only be properly defined as all that contributes to the finer, fuller, richer, wiser, more satisfying living of the race as a whole, and there is scarcely a bit of knowledge of the external world or of man himself that does not definitely help toward

[1] Address before the Society of Chemical Industry, New York, September 4, 1928, on the occasion of the conferring on Dr. Robert A. Millikan of the Messel Medal in honor of his work on the structure and relations of atoms.

that end. Some of the most useful discoveries have exerted their chief influence, not through showing how the yield of beans or of cabbages per acre could be doubled, but rather through preventing mankind from wasting its precious energies on useless undertakings, such for example as building a tower of Babel. All knowledge that helps toward an understanding of the nature of the universe of which we are a part is useful, for we need very much more of it than we now have, or shall have for centuries to come, to enable us to direct our energies toward wise, effective living instead of wasting them on beating tom-toms, inventing perpetual-motion machines, or chasing either physical or social rainbows. "A penny saved is a penny earned," and this is quite as true of human energies as of household economics.

The disasters that can befall mankind merely because of erroneous conceptions of the nature of the world in which we live are well illustrated by the historic record of the miseries that came upon the earth in the year 1000 A. D. because of the widespread belief that the world was coming to an end at that time. The recent exact measurement of the amount of lead in Black Hills uraninite, and of the exact atomic weight of that lead, is not usually regarded as a great engineering undertaking, nor as an accomplishment fraught with important useful consequences; but I venture the estimate that the knowledge that has come from that and similar experiments to the effect that this world has already had a lifetime of at least a billion years, and that man has in all probability another billion years ahead of him, in which there is the possibility of his learning to live at least "a million times more wisely" than he now lives, is likely to have in the long run a much larger influence upon human conduct than the invention either of the airplane or of the radio, important and preeminently useful though these be. Similarly, the discovery of the second law of thermodynamics has been perhaps more useful in preventing useless effort, in spite of the legions of perpetual motion cranks who still infest all physical laboratories, than in improving the efficiency of the heat engine.

The foregoing considerations constitute my argument for the appropriateness of presenting before the Society of Chemical Industry some discoveries that have not heretofore been labelled "useful" but which, when put together and correctly interpreted, as I hope they are herewith, may constitute an important and perpetually burning beacon to point out to mankind the way of progress, even of *industrial* progress.

The four recent developments in the field of pure science that I am herewith endeavoring to fuse together into a result of industrial importance are: (1) the discovery of the relation between mass and energy; (2) the development of methods of making very exact atomic-weight determinations; (3) the discovery of the cosmic rays; (4) the development of relativity—quantum mechanics. It may appear at first sight to the average supporter of Al Smith that I have taken a large order, but pray withhold your judgment.

The first of these four very recent developments was stated in its general equational form, namely, $mc^2 = E$, in which m represents mass in grams, c the velocity of light, and E energy in ergs, by Einstein as one of the most important consequences of the special theory of relativity (1905); but it had been experimentally established for special cases before Einstein's day, namely, in 1901 and 1902 by Kaufmann's measurements on the variation of the mass of the electron with its kinetic energy, and it had also been made by Lorentz a theoretical consequence of the electro-magnetic theory of the origin of mass. This equation may therefore, I think, be taken as a safe practical guide even by those who hope that the special theory of relativity may ultimately be found to involve some second-order error. The Michelson-Morley experiment has surely been sufficiently checked to establish the fact that it involves no first-order uncertainty.

The second of the foregoing developments is due primarily to Aston, of Cambridge University, England, who last summer, 1927, established experimentally a definite relation represented by a smooth curve, between the atomic weights of the elements and the mass of the positive electron as it appears in the constitution of the nucleus of each particular atom. This relation is a purely empirical one, the bearing of which upon the argument herewith presented has never, so far as I know, been pointed out before, at least in a quantitative way, save in very recent papers by Dr. Cameron and myself, the most complete and important of which is to appear in the October number of *The Physical Review*.

The point upon which we lay emphasis is that if this smooth experimental curve may be taken as a safe guide, then by combining it with Einstein's equation we can at once draw very important conclusions about the possible sources of available energy.

The first conclusion that we draw is that *the process of radioactive disintegration with the ejection of an alpha particle is a process that can take place only in the case of a very few of the very heavy and very rare elements.* For radioactivity is a heat-evolving, *i.e.*, an exothermic process, otherwise it of course could not take place of its own accord, and Einstein's equation tells us that no energy-evolving or exothermic process can take place unless the total mass of all the constituents after the change is less than the total mass before the change—that an equivalent mass must

always disappear if other forms of energy are to appear. But the relation of these masses before and after any hypothetical change is just what is given by Aston's curve, which shows that no element of atomic weight under say about 100 can disintegrate with the ejection of an alpha particle and the evolution of energy. And yet more than ninety-nine per cent. of all matter consists of these atoms of atomic weight less than 100. Therefore radioactivity with the ejection of alpha particles, even of a very feeble energy, is not a general property of matter, as many of us have in the past thought it might be. Under the stimulus of the discovery of the enormous quantities of energy evolved in the disintegration of uranium and thorium we have often imagined, and sometimes incautiously stated, that there might be similar amounts of available energy locked up in the common elements, releasable, perchance, by getting them to disintegrate, as uranium and thorium spontaneously are doing. And engineers, physicists and laymen alike have talked glibly about "utilizing this source of energy when the coal is gone." So-called humanists, on the other hand, advocates of a return to the "glories" of a pre-scientific age, have pictured the diabolical scientist tinkering heedlessly, like the bad small boy, with these enormous stores of sub-atomic energy, and some sad day touching off the fuse and blowing our comfortable little globe to smithereens.

But Nature, or God, whichever term you prefer, was not unconscious of the wisdom of introducing a few fool-proof features into the machine. If Einstein's equation and Aston's curve are even roughly correct, as I am sure they are, for Dr. Cameron and I have computed with their aid the maximum energy evolved in radioactive change and found it to check well with observation, then this supposition of an energy evolution through the disintegration of the common elements is from the one point of view a childish Utopian dream, and from the other a foolish bugaboo. *For the great majority of the elements, such as constitute the bulk of our world, are in their state of maximum stability already.* They have no energy to give up in the disintegrating process. They can only be broken apart by working upon them, or by supplying energy to them. Man can probably learn to disintegrate them, but he will always do it "by the sweat of his brow."

But having thus disposed of the process of atomic disintegration, and found it completely wanting as a source of available energy, since the radioactive elements are necessarily negligible in quantity, let us next see what there is to be learned about the process of atom-building as a source of energy. Here Einstein's equation, Aston's curve, and the third of the foregoing developments in pure science, namely, the recent experimental work on cosmic rays, have just thrown a flood of light on the processes going on in this universe in which we live. For, first, Dr. Cameron and I have recently found three definite cosmic ray bands, or frequencies, of penetrating powers, or ray-energies, respectively, twelve, fifty and one hundred times the maximum possible energies that are, or can be, obtained from any radioactive, that is, any disintegrating, process. The highest frequency band has so enormous a penetrating power that it passes through as much as 200 feet of water or eighteen feet of lead before becoming completely absorbed, while two or three inches of lead absorbs the hardest gamma rays. This discovery of a banded structure in cosmic rays shows that these rays are not produced, as are X-rays, by the impact upon the atoms of matter of electrons that have acquired large velocities by falling through powerful electrical fields, as we earlier suggested—the fields needed to produce frequencies as high as those of the highest observed cosmic rays are equivalent to 216,000,000 volts—but that *they are rather produced by definite and continually recurring atomic transformations involving very much greater energy-changes than any occurring in radioactive processes.*

Taking Einstein's equation and Aston's curve as a guide there are no possible atomic transformations capable of yielding rays of the enormous penetrating power observed by us, except those corresponding to the building up or creation of the abundant elements like helium, oxygen, silicon, and iron out of hydrogen, or possibly in the case of the last two elements out of helium. The entire annihilation of hydrogen by the falling completely together of its positive and negative electrons has been suggested as an additional possibility, but it can be eliminated in this case for two excellent reasons. The first is that there is no place for such a radiation to occupy in the observed cosmic-ray curve; and the second is that this radiation, if it were present, would necessarily be homogeneous and could not by any possibility exhibit the banded structure shown by the observed cosmic rays. So that here alone, by a process of exclusion, we have arrived at pretty definite evidence that *the observed cosmic rays are the signals broadcasted throughout the heavens of the births of the common elements out of positive and negative electrons.*

But right here is where the fourth of the aforementioned recent developments in the purest of pure science dovetails into the practical picture. Dirac is a young Englishman deeply versed in all that the engineer of to-day—and even the experimental physicist too—is rather proud to say "is altogether beyond him," meaning thereby that he considers that there are more important things for him to put his energies upon.

Such highbrow subjects as relativity-quantum mechanics, and the new wave-mechanics, to which Dirac has made outstanding contributions—where do they touch life anyway? Very quickly has come the answer. Dr. Cameron and I had measured fairly accurately the penetrating powers, or absorption coefficients, of our three prominent cosmic-ray bands. Without being guided by any theory at all we had found them at $\mu = 0.35$, $\mu = 0.08$, $\mu = 0.04$ where μ means absorption coefficient per meter of water. Dirac's relativity-quantum-mechanics formula, giving the quantitative relation between absorption coefficient and frequency, or energy, this formula being an extension of and correction to one originally worked out with consummate skill by Arthur H. Compton, of Chicago, last year's Nobel-prize winner in physics, enables us to compute accurately from Einstein's equation and Aston's curve what should be the absorption coefficients, or the penetrating powers, of ether-waves produced by the act of creation of the common elements out of the primordial positive and negative electrons.

Before presenting these computations, however, let me build a little more background. It is an interesting and a very important fact from the practical viewpoint, too, that more than ninety-five per cent. of this universe, so far as we can now see, is made up of a very few elements.

First. The spectroscopy of the heavens shows the enormous prevalence everywhere of hydrogen, but hydrogen is merely the primordial positive and negative electrons tied together, or in process of being so tied.

Second. The spectroscopy of the heavens also shows that helium is an exceptionally abundant, and a very widely distributed, element, even though, because of its lightness and inability to combine with anything, even with itself, the earth has not retained much of it. Significant is it, however, that the alpha particle given off by all the heavy radioactive elements is nothing but helium, so that it must have a certain prevalence even on earth in the structure of the heavier elements.

Third. Dr. Bowen, at the California Institute, has just shown that "nebulium," also abundant almost everywhere in the heavens, is nothing but oxygen and nitrogen, while oxygen alone constitutes 55 per cent. of the earth's crust, and about the same proportion of meteorites. Oxygen and nitrogen, then, which for our present purpose will be treated as one element, since they have nearly the same atomic weight and will be henceforth listed under the name of the stronger brother, constitute the third extraordinarily abundant element, and it is to be noted that there are no abundant elements at all between helium and oxygen. Carbon has a certain minor prevalence, but because of its nearness in atomic weight to nitrogen and oxygen it may here be treated as merely a feeble satellite to oxygen.

Fourth. Ninety-five per cent. of the weight of all meteorites consists of oxygen (54 per cent.), magnesium (13 per cent.), silicon (15 per cent.) and iron (13 per cent.), while 76 per cent. of the earth's crust is composed of the three elements, oxygen (55 per cent.), silicon (16 per cent.) and aluminum (5 per cent.), no other element rising over 2 per cent. Iron constitutes 1.5 per cent. of the crust, but it is supposed to be very largely represented in the interior. Because of the closeness in their atomic weights magnesium, aluminum and silicon (24, 27, 28) may, for our present purpose, be regarded as a single element and given the name of the strongest brother, silicon. There are then no abundant elements whatever between oxygen and silicon, nor between silicon and iron (atomic weight 56), *and from an engineering standpoint the universe may be said to be made up of the primordial positive and negative electrons, and of four elements built out of them, namely, helium, oxygen, silicon and iron.*

Let me now digress from my subject, "Available Energy," just long enough to point out the practical significance of the foregoing facts. Mankind, if he is here a billion years hence, will be satisfying his main needs, as he satisfies them now, with the four elements, hydrogen, oxygen, silicon and iron, *i.e.*, with water, air, earth and Fe, where the last symbol stands for iron rather than for fire, which was the fourth constituent of the world of the ancients. These fundamental facts may some time help to stabilize the stock market. Aluminum might some day compete with iron in usefulness if lightness were a desideratum, but for the great bulk of structural purposes it is not. The progress of science and invention is not likely to put out of business for a billion years to come the concerns engaged in the iron and steel industry.

But my subject to-day is not available materials but rather available energy. Einstein's equation and Aston's curve, then, enabled Dr. Cameron and myself to compute the energies sent out in the ether signals arising from the creation in single isolated acts of helium, oxygen, silicon and iron, and then Dirac's formula enabled us to compute the absorption coefficients of the corresponding cosmic rays. The theoretical values of the absorption coefficients corresponding to the first three of these creative acts came out $\mu = 0.30$, $\mu = 0.08$, $\mu = 0.04$, as compared with the previously obtained and already reported observed-values $\mu = 0.35$, $\mu = 0.08$, $\mu = 0.04$. The agreement is better than our observational uncertainty, and leaves no doubt whatever in our own minds that *the observed cosmic rays are in fact the birth-cries of the infant*

atoms of helium, oxygen and silicon. We have some little indications that we can also hear the shriller birth squeaks of infant iron, but we are not yet ready definitely to assert it.

But the question that is already being asked on all hands is "Where are these atom-building processes going on?" To this question, too, we think we have the answer. It is "not at all in the stars," for high temperatures and densities seem to be inimical at least to the process of the creation of the foregoing abundant elements out of the primordial positive and negative electrons. The building of the radioactive elements, which is an endothermic, or energy absorbing, process, may possibly be taking place in the stars where surplus energy is available for it. We have no experimental evidence whatever on this point. But we have what we consider excellent experimental proof that the foregoing endothermic processes that produce the cosmic rays do not take place in the stars at all. The full argument is given in the October issue of *The Physical Review,* but the fact that the sun, the great hot mass just "off our bows," has no influence whatever upon the intensity of the observed cosmic rays, for these come in just as strong at midnight as at noon, is enough to show that this particular star is not a source of cosmic rays. Since, however, these rays do come in to us all the time, and practically uniformly from all directions, Dr. Cameron and I can find no escape from the conclusion that these atom-building processes which give rise to the observed cosmic rays are favored by, and actually have their source in, the places in the universe where the temperatures and pressures are extreme in the opposite sense, *i.e.,* where they are close to absolute zero. In other words, *we think that the atom-building processes that give rise to the observed cosmic rays can take place only under the extreme conditions of temperature and pressure existing in interstellar, or intergalactic,* space.

Now combine this conclusion with that already arrived at by astronomers like Eddington and Jeans, who can find no way of accounting for the immense quantities of energy which for billions of years have been poured out by the sun and other stars, save in the assumption that under the conditions of stupendous temperatures and pressures existing at or near their centers mass is being wholly converted into radiant energy by the complete falling together of positive and negative electrons. If this is a correct conception, and it has become orthodox astronomy, then the combination of it with the cosmic-ray evidence herewith presented *leads to the picture of a continuous atom-destroying process taking place under the extreme conditions existing in the interior of stars, and an atom-creating process continually taking place under the equally extreme conditions of just the opposite sort existing in interstellar space.* Let us analyze a little further these two processes.

The process in which positive and negative electrons under the influence of the stupendous temperatures and pressures existing in the interiors of stars completely fall together—this need happen only occasionally in the interior of very heavy atoms, heavier, Jeans thinks, than any existing on the earth—must in any case, as we find from Einstein's equation, be one that gives rise to an ether-wave about four times as penetrating as the most penetrating cosmic ray thus far observed. We have looked diligently for a cosmic ray of this sort, but it definitely does not appear in our cosmic-ray curves. This is, however, to be expected, since, according to its sponsors, it is formed only in the interior of stars, and hence is hidden away behind an impenetrable screen of matter that completely transforms it into heat before it gets out. Indeed, in accordance with the Jeans-Eddington theory this is merely the way the furnaces of the stars are continually being stoked and all that we ought to observe is the heat and light that they radiate in consequence.

The continuous formation, however, of the common elements in interstellar space newly and directly observed through the cosmic rays thereby sent forth raises imperiously the question as to why the primordial positive and negative electrons, which are the building stones of these common atoms, have not long ago been used up, since the process has undoubtedly been going on for eons upon eons. And the answer that Dr. Cameron and I wish to make is that out in the depths of space, where we actually observe, through the cosmic rays, helium, oxygen and silicon being continually formed out of positive and negative electrons, there too these positive and negative electrons are also being continually replenished through the conversion back into them, under the conditions of zero temperatures and densities existing there, of the radiation continually pouring out into space from the stars. With the aid of this assumption we are able to regard the universe as in a steady state now, and we are able also to banish forever the nihilistic doctrine of its ultimate "heat-death."

We regard our assumption as the least radical and the most satisfactory of any of the three between which, in any case, a choice must be made.

1. The first of these is that of Jeans,[2] that mass, *i.e.,* the electron (positive and negative alike) is convertible into radiant energy, *but that the process is nowhere reversible.* Matter will thus ultimately be all converted into radiation, *i.e.,* it will simply disappear. A recent statement of Jeans' reads: "Thus observation

[2] J. H. Jeans, Nature, *121,* 467, 1928.

and theory agree in indicating that the universe is melting away into radiation. Our position is that of polar bears on an iceberg that has broken loose from its ice pack surrounding the pole, and is inexorably melting away as the iceberg drifts to warmer latitudes and ultimate extinction."

This is the old hypothesis of the "heat-death." It conflicts with no observed facts, and before the advent of Einstein it was a necessary consequence of the Second Law *provided the universe were treated as a closed system.* Scientists, however, have always objected that such treatment represents an extravagant and illegitimate extrapolation from our very limited mundane experience and modern philosophers and theologians have also objected on the ground that it overthrows the doctrine of Immanence and requires a return to the middle-age assumption of a *Deus ex machina.* Since the advent of Einstein it meets the further difficulty that it injects into modern thermodynamics one single process—the convertibility of mass into radiant energy—which violates the principle of "microscopic reversibility" required by the modern statement of the Second Law.

2. The second possible hypothesis is that of Stern,[3] Tolman[4] and Zwicky,[5] that the foregoing processes are all everywhere reversible. This hypothesis keeps the second law intact, including microscopic reversibility denied by Jeans' assumption, but so far as we can now see it does not avoid the "heat-death," and it is not favored by the evidence herewith presented that the atom-building processes that give rise to the cosmic rays do not seem to be taking place everywhere, *e.g.,* in the stars, but do seem to be taking place solely in the depths of space.

3. The third hypothesis—that herewith presented—is just as radical as 1, but no more so, in denying microscopic reversibility, but it provides an escape sought in vain by both 1 and 2 from the "heat-death." Also it is just as radical as 2, but no more so, in assuming that radiant energy can condense into atoms somewhere, but it is in better accord with the cosmic-ray evidence that the atom-creating processes seem to take place only in interstellar space.

But if the point of view developed in the foregoing is correct what sources of energy are there, then, for man to draw upon during the next billion years of his existence? The answer has already been given but it may be restated thus:

(1) The energy available to him through the *disintegration* of radioactive, or any other, atoms may perhaps be sufficient to keep the corner peanut and popcorn man going, on a few street corners in our larger towns, for a long time yet to come, but that is all.

(2) The energy available to him through the *building-up* of the common elements out of the enormous quantities of hydrogen existing in the waters of the earth would be practically unlimited provided such atom-building processes could be made to take place on the earth. But the indications of the cosmic rays are that these atom-building processes can take place only under the conditions of temperature and pressure existing in interstellar space. Hence there is not even a remote likelihood that man can ever tap this source of energy at all. The hydrogen of the oceans is not likely to ever be converted by man into helium, oxygen, silicon or iron.

(3) The energy supplied to man in the past has been obtained wholly from the sun, and a billion years hence he will still, I think, be supplying all his needs for light, and warmth, and power entirely from the sun. How best to utilize solar energy it is not the purpose of this paper to reveal. That subject is treated in masterly fashion in a paper by Edwin E. Slosson entitled "The Coming of the New Age of Coal," printed in the *Proceedings* of the International Conference on Bituminous Coal held from November 15 to 18, 1926—a paper to which I refer the reader for the next chapter on "Available Energy." The present paper serves merely as an introduction to Dr. Slosson's.

(4) When the matter of the sun has all been stoked into his furnaces and they are gone altogether out another sun will probably have been formed, so that on this earth or on some other earth—it matters not which some billion of years hence—the development of man may still be going on.

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[3] O. Stern, Zeit. f. Elektrochemie, *31,* 448, 1925.

[4] Richard C. Tolman, Proc. Nat. Acad. Sci., *12,* 67, 1926; *14,* 268, 348, 353, 1928.

[5] F. Zwicky, Proc. Nat. Acad. Sci., *14,* 592–597, 1928.

THE RELATION OF PHYSIOLOGY TO OTHER SCIENCES—II

SCIENTIFIC ASPECTS

PHYSIOLOGY takes its place as a science in proportion as its data are accurate and its principles fall into line with those in the other sciences. My great teacher Starling said that science has only one language, that of quantity, and but one argument, that of experiment. The qualitative observations of one generation tend to become quantitative at a later stage of development of a science, and the degree of development of a science can indeed to some extent be judged by the extent to which it falls into a scheme of the