SCIENCE

VOL. 94 FRIDAY, SEPTEMBER 5, 1941 No. 2436

SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. MCKEEN CATTELL and published every Friday by

THE SCIENCE PRESS

Lancaster, Pa. Garrison, N. Y.
New York City: Grand Central Terminal

Annual Subscription, $6.00 Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the Association may be secured from the office of the permanent secretary in the Smithsonian Institution Building, Washington, D. C.

THE NEW FRONTIERS IN THE ATOM[1]

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THE anniversary celebration of a great university is indeed an important occasion, and it is appropriate to signalize the event by a symposium on "The University and the Future of America," for a great institution of learning is eternally youthful, and youth looks always to the future. I am greatly honored to be included in this distinguished gathering, and it gives me especial pleasure to join in wishing our sister institution many happy returns.

In a discussion bearing on the future, the scientist is always in something of a dilemma. On the one hand, he is cautioned to make only very limited prognostications, for he has learned the very limited region of applicability of existing knowledge and the likelihood of error in speculation. On the other hand, he faces the future with eager excitement and curiosity about what is beyond the present frontiers of knowledge, and he is naturally tempted to speculate and indeed to indulge in daydreams. Perhaps I may convey something of what is in the minds of physicists these days by a brief discussion of some recent developments of the current intensive attack on the new frontier in the atomic world—the nucleus of the atom.

ATOMS

The atomic constitution of matter has long been a keystone of natural science. At the beginning of this

[1] An address delivered at the fiftieth anniversary celebration of Stanford University, June 16. It will appear with illustrations in a volume to be published by the Stanford University Press.

century it was a keystone in a structure having as pillars the principles of the conservation of energy and the indestructibility of matter. In the nineties, it was almost axiomatic to say that the building blocks of nature are the atoms—indivisible, indestructible entities, permanent for all time. But the discovery of radioactivity altered all this. There followed the discovery of the electron and the proton as smaller and more fundamental constituents of matter and the atom itself became the happy hunting ground of the experimental physicist. Atomic physics developed rapidly; for the atom was found to be a domain of almost incredible richness, and to-day, thanks perhaps to the newspapers, our children speak knowingly of smashing atoms!

To explain the wonderful phenomena of radioactivity, Rutherford came forward in 1904 with a revolutionary hypothesis which reduced the complicated and mysterious observations of radioactivity to simple order. According to Rutherford, not all the atoms have existed for ages and will exist for all time, but there are some atoms in nature that are energetically unstable and in the course of time, of their own accord, blow up with explosive violence. These are the natural radioactive substances, and the fragments given off in the atomic explosions are the observed penetrating rays.

It was not long before Rutherford's hypothesis was established as a law of nature and formed a greater keystone, replacing the chemists' conception of the atom and serving as a foundation for a new science, the science of the atomic nucleus.

Time does not permit an adequate historical résumé of the development of nuclear physics, but for the present purpose it is sufficient to say that the ideas of Rutherford and Bohr on the structure of atoms are now firmly established. There is an abundance of evidence that an atom consists of a nebulous cloud of planetary electrons whirling about a very dense sun, the positively charged nucleus, and that it is in the nucleus that the atomic explosions of radioactivity occur. Indeed, our assurance that this is so rivals our confidence that the planets revolve about the sun!

Atomic Nucleus

Let us now proceed immediately to a consideration of the structure of the nucleus. The nucleus consists of a closely packed group of protons and neutrons, elementary building blocks of nature some 2,000 times heavier than the electrons. The neutrons are electrically neutral while the protons carry positive charges and for each proton in the nucleus there is a corresponding negative electron outside, for the atom as a whole is uncharged. Since the number of electrons outside determines the ordinary chemical and physical properties of the atom, it follows that the nuclear charge determines the place of the atom in the periodic table of the elements.

Thus, the nucleus is the body and soul of the atom. More than 99.9 per cent. of the atom's mass is in the nucleus and the nuclear charge determines the nature of the atom, its chemical and physical properties.

Transmutation of the Elements

These considerations reduce the age-old problem of alchemy to simple terms. For we see to change one element into another is simply to change the nuclear charge, *i.e.*, the number of protons, in the nucleus. The subject of transmutation of the elements has recently received a great deal of attention in the laboratory. All sorts of transmutations have been produced in a minute scale—helium has been made from lithium, magnesium from sodium and even mercury has been turned into gold. The day may come when we will indeed possess the philosopher's stone and will be able to transmute the elements on a grand scale. But interesting as these developments are, I should like to draw your attention to two other subjects, artificial radioactivity and the question of tapping the vast reservoir of energy in the nucleus of the atom.

Artificial Radioactivity

One of the early results of atomic bombardment was the discovery that neutrons could be knocked in or knocked out of the nucleus to produce radioactive isotopes of the ordinary elements. Thus, for example, the nucleus of the ordinary sodium atom contains 11 neutrons and 12 protons, 23 particles in all, and so it is called sodium 23 (or Na^{23}); and by bombardment it was found that a neutron could either be added to make sodium 24 or subtracted to make sodium 22, both isotopic forms not occurring in the natural state. The reason that these synthetic forms are not found in nature is that they are energetically unstable. They are radioactive and in the course of time blow up with explosive violence. Sodium 24 has a half-life of 14.5 hours, *i.e.*, it has an even chance of disintegrating in that time, turning into magnesium by the emission of an electron. Sodium 22, on the other hand, has a half-life of 3 years and emits positive electrons to turn into stable neon 22.

These artificial radioactive isotopes of the elements are indistinguishable from their ordinary stable relatives until the instant they manifest their radioactivity. This fact deserves emphasis, and it may be illustrated further by the case of chlorine. Chlorine consists of a mixture of two isotopes, 76 per cent. of Cl^{35} and 24 per cent. of Cl^{37}, resulting in a chemical atomic weight of 35.46 which is the average weight of the mixture. By elaborate technique, to be sure, it is possible to take advantage of the extremely slight difference in chemical properties and bring about separation of these isotopes, but in ordinary chemical, physical and biological processes, the chlorine isotopes are indistinguishable and inseparable. The artificial radioactive isotopes Cl^{34} and Cl^{38} are likewise indistinguishable. In fact, Cl^{34} is more nearly identical in properties to the natural isotope Cl^{35} than is the other natural isotope Cl^{37}. And again I would say that the radioactive characteristic of Cl^{34} becomes evident only at the moment it blows up to turn into the neighbor-element sulfur.

RADIOACTIVE TRACER ATOMS

In these radioactive transformations of the artificial radioactive isotopes, the radiations given off are so energetic that the radiations from individual atoms can be detected with rugged and reliable instruments, called Geiger counters. Thus, radioactive isotopes can be admixed with ordinary chemicals to serve as tracer elements in complicated chemical or biological processes.

As an illustration of the power of this new technique of labeling and tracing atoms, let us consider iodine in relation to the thyroid gland. It is well known that the thyroid takes up and stores iodine, and this fact can be demonstrated strikingly by feeding an individual iodine including a small quantity of radioactive iodine. Before the feeding, the radioactivity of the food can be measured by placing it near a Geiger counter, thereby giving a measure of iodine content. Later the progress of the iodine through the body can be observed by placing the Geiger counter next to various parts of the body. Likewise, the proportion of the fed iodine in the various body fluids at any time can be determined quickly by taking small samples of the fluids and measuring their radioactivity. After some hours it is found that a large part of the iodine taken in has collected in the thyroid, a fact that is readily established by placing a Geiger counter next to the gland [lantern] and observing the activity while finding no appreciable activity elsewhere. This technique makes it possible to study the behavior of the thyroid in health and in disease, and much interesting work along this line has been carried out recently.

RADIO-AUTOGRAPHY

Although the tracer elements are readily detected with the Geiger counter, there is a photographic method which for many purposes has obvious advantages. This method is sometimes called radio-autography and is illustrated by the lantern slide. Here a minute amount of radioactive phosphorus in the form of sodium phosphate was added to the nutrient solution of a tomato plant, and after a day or so leaves were placed against a photographic film enclosed in a light-tight paper envelope. The penetrating rays from the radioactive phosphorus produced the developed contact image shown, which gives an accurate and detailed picture of the uptake of phosphate by the plant. Now, indeed, the same method works very well also for the thyroid, as is shown in the lantern slide, which is a photomicrograph of a thin section of thyroid tissue containing radio-iodine; alongside is the radio-autograph obtained from the same micro section by placing it against a photographic plate. The distribution of the iodine in various parts of the gland is shown in surprising detail.

Similarly striking radio-autographs of the distribution of phosphorus and strontium in rats are shown in the lantern slide. Here two rats were fed radio-phosphorus and radio-strontium respectively, and then some hours or days later they were sacrificed, and frozen sections of the entire bodies of the animals were placed against a photographic plate. The resulting radio-autographs show clearly that both strontium and phosphorus are selectively deposited in the bones, phosphorus being more widely distributed in other tissue. The distribution of the strontium in the bones also appears to be quite different from that of phosphorus as radio-autographs of the sections of bones clearly show [lantern].

These examples serve to illustrate the power of the new technique of radioactive tracer atoms. It has often been said that the progress of science is the progress of new tools and new techniques, and I think we may look forward to accelerated developments in biology resulting from the tracer elements.

ARTIFICIAL RADIOACTIVE SUBSTANCES IN THERAPY

It is somewhat afield for me to discuss medical problems, but I should like to direct your attention to the possibilities of the artificial radioactive substances in the treatment of cancer and allied diseases. It is well known that at the present time there are two main approaches to the treatment of neoplastic disease, surgery and radiation. It is sometimes possible to cut out a cancer completely and effect a cure, and in other circumstances, it is possible to destroy a tumor by irradiation with x-rays or radium. The mechanism whereby the radiation destroys the tumor without destroying an excessive amount of surrounding normal tissue is doubtless extremely complicated, but in any case it is evidently important to localize the radiation to the tumor as much as possible. Perhaps the ideal would be approached if a means were at hand to irradiate each and every malignant cell without irradiating a single normal cell.

The artificial radioactive substances open for the first time the possibility of an approach to such selective irradiation of tissue. The above examples of tracers suggest the treatment of thyroid tumors with radioactive iodine, bone tumors with radioactive strontium and radioactive phosphorus. These possibilities are being investigated as is the more specific problem of finding a radioactive substance that is selectively taken up by tumor tissue. If there were time, I should like to describe work along this line in progress in several laboratories, and especially to speak of the important progress that is being made in the treatment of leukemia, but I must content myself with only mentioning these new developments in medicine, which are so promising for the future.

ATOMIC ENERGY

For a long time astronomers have been vexed with a problem, the problem of the source of stellar energy, for there is evidence that the sun has been blazing at its present brilliance for thousands of millions of years, and no ordinary fuel could be responsible for such an eternal fire.

The discovery of radium posed to the physicist a similar difficulty; for it was found that radium gives off every hour enough energy to heat its own weight of water to boiling, and this it continues to do for more than a thousand years. Such a vast source of energy in the radium atom was as difficult to understand as the evidently limitless store of heat in the sun. The problem was of fundamental interest and all sorts of possibilities were considered even to the abandonment of the principle of the conservation of energy.

But the first clue to the solution of the problem appeared in 1905 when Einstein announced the theory of relativity. One of the revolutionary consequences of the theory was that matter is a form of energy and that presumably in nature processes go on in which matter is destroyed and transformed into more familiar forms of energy such as heat, radiation and mechanical motion. The relativity theory gave as the conversion factor relating mass to equivalent energy, the square of the velocity of light, a very large number, even to an astronomer! Thus, the theory indicated that, if a glass of water were completely destroyed, more than a billion kilowatt hours of energy would be released, enough to supply a city with light and power for quite a time!

This exciting deduction was immediately accepted by the astronomers, who said, "Doubtless within the sun conditions are such that matter is being transformed to heat. Thus, slowly through the ages the sun is losing mass; its very substance is radiating into space."

Likewise, the physicists, who had other compelling reasons for accepting the Einstein theory, concluded that the source of the energy in the radium atom was a destruction of matter in the atomic explosion giving rise to the penetrating rays.

Although the fundamental assumptions on which the relativity theory was based were evidently sound, and the explanations of the source of energy of the sun and stars and radioactivity were most attractive, until direct experimental verification was forthcoming, Einstein's great deduction could not be regarded as an established law of nature.

The first direct evidence of the truth of this fundamental principle was obtained in the first atom-smashing experiments a decade ago. It was observed that, when the nucleus of a lithium atom is hit by a proton having a kinetic energy of less than a million electron-volts, the result is the formation of two helium nuclei which fly apart with an energy of more than 17 million electron-volts; thus in the nuclear reaction in which hydrogen and lithium unite to form two helium atoms, there is a great release of kinetic energy.

Now one of the interesting and important occupations of the experimental physicist has been the measurement of the masses of atoms and the weights of atoms are known with great precision—much greater than any individual knows his own weight. In particular, it was known precisely that a lithium atom and a hydrogen atom have a total weight slightly greater than the weight of two helium atoms, and it was a great triumph for the Einstein theory when measurements showed that the excess kinetic energy with which the helium atoms flew apart in the hydrogen-lithium reaction corresponded exactly with the disappearance of mass according to the mass energy relation. Literally hundreds of similar nuclear reactions have been studied in the intervening years, and in each instance the Einstein relation has been verified. At the present time this great principle has as firm an experimental foundation as any of our laws of nature.

URANIUM FISSION

Now that it is an experimental fact that matter can be converted into energy, it becomes of great practical importance to inquire whether the vast store of energy in the atom will be tapped for useful purposes. This question has recently taken on added interest through the discovery of a new type of nuclear reaction involving the heavy element uranium.

It has been known for some years that the heavy elements, such as lead, gold and uranium, are relatively heavier than the middle weight elements, as copper and iron, or more precisely that the average weight of the neutrons, protons and electrons in the heavy elements is greater than their average weight in the atoms near the middle of the periodic table. Accordingly, it is to be expected that, if heavy atoms were split approximately in two, forming corresponding middle weight atoms, there would be a vast release of energy corresponding to the disappearance of matter in the transformation. Indeed, from known values of the masses, it can be calculated on the basis of Einstein's mass-energy relation that each splitting or fission, as the process is called, of a uranium atom into two approximately equal parts releases an energy of about 200 million electron-volts, which is millions of times more heat per atom than is given off when ordinary fuel is burned. Thus, calculations show that 100 pounds of uranium would yield a billion kilowatt hours, which at one cent per kilowatt hour would be ten million dollars' worth of electrical energy.

For some time these considerations were largely academic because no way was known for producing fission of the heavy elements. But interest in the matter has now become extremely lively as a result of the discovery that fission of uranium is actually brought about by bombarding it with neutrons.

The phenomenon has, during the past two years, received intensive study in laboratories all over the world, and several salient facts have emerged. First, the rare U^{235} isotope undergoes fission after absorption of a slow neutron. Second, the energy released in the fission process has been measured; and, as expected, it is found that, when a neutron having an energy less than an electron-volt enters the U^{235} nucleus, about 200 million electron-volts of energy is released. Third it is found also that the fission process is so violent that usually the U^{235} nucleus does not break up into two parts only, but more often several neutrons are given off in addition to the two large fragments.

That neutrons are generated in the fission process is of the greatest interest because it opens up the possibility of a chain reaction, a series of nuclear reactions wherein the neutrons liberated in one fission process go on to produce additional fissions in other atoms which in turn give rise to more neutrons which produce further fissions and so on. It is this possibility of a chain reaction that has excited the interest in uranium as a practical source of atomic energy.

Without going into further detail, it is perhaps sufficient to say that there is some evidence now that, if U^{235} could be separated in quantity from the natural mixture of the isotopes, a chain reaction could, indeed, be produced. But herein lies the catch, for there is no practical large-scale way in sight of separating the isotopes of the heavy elements, and certainly it is doubtful if a way will be found.

But I should not want to indicate that the uranium matter is a disappointment, that after all we shall never find a way to bring about fission of the heavy elements for useful purposes. Quite the contrary!

The present situation is not unlike the circumstances fifty years ago surrounding the then great question of whether man would ever be able to fly. In those days the fundamental laws of classical mechanics were known, and they allowed the possibility of heavier than air flight. Moreover, there was an abundance of supporting observational evidence that flight should be possible; there were kites and there were the birds of the air. But man's realization of the dream awaited primarily the development of the combustion engine, a circumstance not so evidently connected with the fundamental problems of flight. Likewise the fundamental laws of nature recently revealed to us allow the possibility of obtaining useful nuclear energy, and radium and the sun and stars bear witness that this vast source of energy is being tapped in nature. Again success in this direction may await the development of a new instrument or technique just as the airplane depended on the gas engine.

Perhaps the problem awaits a deeper understanding of the forces that hold nuclei together. That there are little understood forces operative in the nucleus is more than evident; especially from observations of the cosmic rays, it has been established that particles of matter called mesotrons of intermediate mass between electrons and protons play a dominant role in nuclear structure. Theoretical considerations suggest that the mesotrons may be connected with the primary forces in the nucleus, and accordingly, an understanding of mesotron forces may ultimately yield the solution of the practical problem of atomic energy.

THE GIANT CYCLOTRON

In order to study experimentally the mesotron problem, it is necessary to bombard nuclei with atomic projectiles having energies in the range of 100 million electron-volts rather than in the neighborhood of 10 million electron-volts at present available in cyclotron laboratories. To this end a giant cyclotron is now under construction on Charter Hill in Berkeley, and I should like to conclude with some pictures of this great machine. Whether it will be the key to the vast store of energy in the atom, what new discoveries, what new insight into nature it will bring—only the future will tell!