DETECTING ATOMIC PARTICLES

by ***Serge A. Korff***

The atom, which used to be simple, has become a composite of many different kinds of parts. A nuclear physicist reviews the manner in which atomic particles can be identified.

Physics today knows a whole variety of particles. It deals with protons, positive and negative electrons, neutrons, mesotrons, alpha particles, photons (which are not really particles but are detected by similar means), and deuterons.

These particles, their nature and their number, are ordinarily detected by the trails they leave in passing through a gas or photographic emulsion. The trails come from ionization, an effect which one can measure and observe. Ionization means any process whereby an atom or molecule, originally neutral, acquires a charge. To use it in its broadest sense here, it will also be meant to include electrons ejected from a surface under bombardment.

Ion Trails as Evidence

The alpha particle, or helium nucleus, is a composite made up of two protons and two neutrons, but it enters directly into so many experiments, and it plays so large a part in the structure of matter, that we are including it with the elementary particles. Its two properties of importance in detection are charge and mass: its charge is equal to two positive electronic charges, and its mass is approximately four proton masses. As particles go, this particle is heavy, so its velocity is low compared to that of lighter particles with the same kinetic energy. Indeed it must have kinetic energies of the order of billions of electron volts before its velocity approaches the relativistic limit of light. Since few alpha particles today in practice attain such high energies, we need not concern ourselves with relativity effects, but may, instead, think of the alpha particle simply as a heavy, slow-moving particle.

Now it is precisely such a heavy, slow-moving particle which is an efficient ionizer. The alpha particle leaves behind it, as it plows through a gas, a dense plume of ions. It may leave behind as many as 34,000 ion-pairs in advancing one centimeter through air at standard temperature and pressure. About thirty electron volts is the energy needed to produce one ion-pair, so the alpha particle may expend as much as a million electron volts per centimeter. This is a very high rate of energy-loss, and is indeed ordinarily not exceeded unless one considers fission fragments or nuclear disruptions such as are produced by cosmic rays at high elevations.

Alpha particles are therefore detected by looking for particles which ionize very heavily.

The electron can have either a positive or negative charge, and has a mass about 1/1837th of a proton. Because of its low mass, an electron can approach the speed of light when its energy reaches about half a million electron volts, and with this particle relativity effects are important. An electron with ten million electron volts of energy will have a mass about twenty-two times as great as it has when at rest! But the electron, even when it is moving fast, produces very much less ionization than the alpha particle; indeed at an energy of half a million electron volts it will produce only some thirty ion-pairs for each centimeter of its path through air at standard temperature and pressure. The rate of energy loss is only about one thousand electron volts per centimeter, or about one-thousandth as much as the alpha particle.

An electron has another property which helps to identify it. If it is suddenly decelerated, it will radiate. The energy lost in this manner may be considerable, in fact it may be up to the entire kinetic energy which the electron has. Now, when an electron moves through a crowd of atoms, there is always a chance that it will collide head-on and be decelerated. Thus electrons may be detected not only by their ionization, but by the photons or x-rays they originate.

A beam of electrons passing through matter will in general be accompanied by a beam of photons or x-rays and will not ionize very heavily.

Next we come to the mesotron, often called the meson. This particle is about 200 times as massive as the electron, although its exact mass is still being debated. It may be either positive or negative. Being more massive than the electron, it does not reach relativistic speeds until its energy is some two hundred million electron volts. At these energies, it ionizes about as does the electron, but it does not radiate as much.

A beam of mesotrons passing through a detector may be distinguished from electrons by the absence of evidence for photons.

We now come to a particle or particles about which much debate is still going on. These are neutrinos or neutrettos. These particles are postulated to explain conservation of energy (and spin) in various nuclear transformations. They apparently do not produce appreciable ionization and hence have not been observed directly and unambiguously.

Neutrons, on the other hand, are important and are readily detected. These particles have just about the same mass as protons, but no charge. As neutrons pass through a gas they ionize it hardly at all. Only very occasionally will one make a direct collision with a charged particle, which then recoils, ionizing the gas along its path. Neutrons, however, produce other nuclear effects which are usually ionizing. They are eventually captured by nuclei, and the capturing nucleus, in most cases, gives off ionizing radiation. In some cases the nucleus may become radioactive and decay with electron emission after a half-life which may vary from a fraction of a second to thousands of years. In other cases the disintegration is immediate and the nucleus flies apart at once. In either event, it is the particles emerging from the nucleus which are detected and measured, rather than the neutron itself.

As an example, a neutron may be captured by a boron nucleus. In this case, an alpha particle emerges and may be detected by the usual means employed for other alpha particles. If a neutron is absorbed by silver, a delayed electron emission results. In this case a silver sheet is used as a detector. It is activated by being placed where the neutrons are, and is then moved to an instrument capable of detecting emitted electrons. Thus the amount of electron activity is measured.

To the aggregate of material particles we must add one entity which purists will insist may not be called a particle at all. Yet on occasion it exhibits certain of the properties which we usually ascribe to particles, namely the ability to transmit energy and momentum in collisions which remind us of billiard-ball mechanics. This entity is the photon, or quantum of electromagnetic radiation. It appears in many experiments, and because it ionizes it may confuse the interpretation, so we must include it in our discussion.

A photon may produce ionization in a variety of ways. It may cause the ejection of electrons from the metal walls of the detecting vessels, or from the

Continued on page 25

PARTICLES *Continued from page 13*

atoms at random in a gas. It may also produce electron-pairs, if it has energy enough. The energy necessary varies with the target atom, but it is generally in the neighborhood of twenty million electron volts. If the photon has much more energy than this, the electrons it produces may in turn radiate quanta with energy sufficient again to produce pairs, and so on. This process is cumulative, and is called a cascade.

High-energy photons are often identified by the cascades which accompany them. But the cascades involve both photons and electrons. Either one, if of high enough energy, will produce a cascade, so one cannot deduce whether a cascade was originated by an electron or by a photon.

Photons may also, in the Compton Effect, collide with electrons and transfer substantial amounts of energy to them. These electrons may later ionize or radiate. Thus, in all, photons will lose energy by producing photo-ionization, by producing Compton electrons, and by producing electron-pairs.

The remaining particles are the proton and deuteron. The proton, or hydrogen nucleus, is an elementary particle of single positive charge. It ionizes somewhat less than the alpha particle, but more heavily than the electron. Hence it may be detected by looking for an ionization intermediate between the two. In the energy-ranges usually studied, it does not radiate appreciably. The deuteron (heavy-hydrogen nucleus) is detected by similar means.

Counters, Chambers, and Emulsions

Suppose we put an insulated electrode inside a vessel and maintain a potential difference between the electrode and the vessel's walls. Now any ions produced in the vessel will drift to the wall or to the electrode, depending on whether they are positive or negative. Suppose further that the electrode is positive with respect to the walls. Electrons will drift to the electrode and be collected by it, and positive ions will drift to the walls.

The arrival of electrons at the central collecting system changes the potential of the central electrode. This change can be measured in a variety of ways, as, for example, by connecting the central electrode to a sensitive electrometer, or to the grid of a vacuum tube. The total change in potential is proportional to the total amount of ionization produced, and from the amount of ionization, the nature of the particle is inferred. Such a device is called an ionization chamber.

The total ionization will be determined by the number of ionizing particles, multiplied by the ionization produced by each. In some cases, we wish to know the total ionization, and assume that all or most of the particles are of the same type. For example, in x-ray protection, we assume that the ionizing particles in the chamber are photons and electrons, and we wish to know how much ionization is produced to be sure safe levels are not exceeded. It therefore suffices to measure totals, without any attempt at determining the ionization produced by any single particle. The instrument should thus be very slow in returning to normal from the change in potential produced by the ions so that it can sum up, or integrate, all the ionization arriving on the electrode over a long period of time. This instrument is said to have a long time-constant and can measure the total ionization produced per minute or per hour.

On the other hand, for other applications, we might want to know the amount of ionization produced by each particle, or alternatively, the number of particles. The integrating chamber may be converted to a counting chamber by making the time constant short so that the central collecting system recovers very quickly once it has collected the ions produced by one particle. Then the amount of ionization produced by each particle passing through the chamber is represented by a brief pulse in the potential of the electrode. We may then count numbers of pulses electrically, or numbers greater than a certain size, or we may measure the size of the pulse. A number-size distribution is usually obtained and from this can be inferred the nature of the particles. The operation of a pulsing chamber, incidentally, presupposes that all the ionization produced in one event is collected before the next event occurs. This usually means that pulsing-chambers are operated at higher potentials than are integrating chambers so that the chamber is swept clear of ions between events.

An ingenious modification, which makes the chamber more sensitive, is to use a thin wire for the central collecting electrode. Then, as the electrons drift in toward the central wire, they enter a field which increases as the electron approaches the wire. The electrons move faster and faster until they gain enough energy to produce ionizing collisions on their own account. Half of the newly formed ions drift toward the central wire and many more electrons arrive there than were produced by the original particle. The pulse will be bigger, and less external amplification will be needed to detect it. Amplification, in this case, actually takes place in the gas of the chamber itself.

If this amplification is moderate, then all pulses will be amplified by the same amount and may be used as the basis for distinguishing particle types. This device is called a proportional counter. We can also use it to count the numbers of particles producing more than any given amount of ionization. If such a chamber or counter is exposed to a flux of mixed electrons, protons, and alpha particles, then there are a number of large pulses corresponding to the heavily ionizing alphas, a number of intermediate size produced by the protons, and a set of smaller ones due to the electrons. The device will then tell us how many of each we have.

Amplification is most simply increased by merely increasing the collecting voltage. Above a certain voltage so many ions rush toward the central wire they produce a significant field on their own account which repulses ions of like sign. This effectively reduces the collection voltage. This cloud of ions is called a space-charge sheath and is one of the characteristics which produces saturation at higher amplification. The net result is that pulses no longer grow in a manner proportional to the initial amount of ionization, but eventually all pulses registered are the same size no matter how little or how much was originally produced by a particle. The counter now counts numbers of particles, without distinguishing whether the pulse is produced by an electron leaving a mere dozen electrons behind it or by an alpha particle leaving tens of thousands. The device is then called a Geiger counter, after H. Geiger who first with Rutherford, and later with Müller, studied the properties of the instrument.

Counters are therefore suitable for detecting any type of particle, for any entity which produces ionization will produce a pulse in the counter. Neutrons, for example, are detected by coating the inside of the counter with boron, or using a boron gas for a filling. The boron captures the neutron, and emits an alpha particle which in turn produces ionization and hence initiates a count.

If we want to count a few neutrons in the presence of many electrons or photons, a quite usual situation near a large accelerating device, the counter may be operated as a proportional counter. The electrons produce small pulses and the neutrons large pulses. By electrically rejecting the small pulses the neutrons can be measured in spite of considerable background.

The next type of device used for measuring ionization is the cloud chamber. If a volume of gas containing some liquid vapor is suddenly expanded, the temperature will drop. If this temperature drop brings the gas below the dew-point, the vapor will condense out if dust or ions are floating about in the gas. If, before this expansion, an alpha particle has just passed through the vessel, and left behind it a trail of ionized gas, there will be abundant centers about which condensation will take place and the condensation will look like a trail of fog along the path which the alpha particle followed. Thinner trails will be left by electrons or mesotrons. The tracks are usually photographed, to facilitate measurement, by timing the photograph to take place just after the chamber has been expanded. An experienced cloud-chamber man can tell at a glance what sort of particle was involved.

Cloud chambers have two additional modifications which may be used for particle identification. An absorber such as a lead plate may be placed inside the chamber and its effect on particles traversing it may be noted. Electrons are distinguished from mesotrons by this procedure, for electrons will usually be accompanied by a cascade shower, while mesotrons will penetrate considerable thicknesses of lead without producing high energy electron secondaries.

Another modification of the cloud chamber, which makes it useful for energy measurement, is to apply a magnetic field. Now a charged particle moving in a magnetic field is deflected so that particles passing through the chamber at right angles to the magnetic field will be deflected into orbits which are parts of circles. The radius of the circle is proportional to the momentum of the particle and a simple measurement gives the data for determining its energy. The thickness of the track it leaves identifies it.

If nuclear reactions take place in the chamber, then both the projectile particle and the fragments emerging from the target can usually be identified. Neutrons will not leave trails, but may produce recoils, and disintegrations do leave regular and easily identified cloud tracks. Similarly, photons do not leave cloud trails, but may originate cascade showers if of high energy, or they may originate photo-electrons or Compton recoil electrons at both high and low energies.

The last important type of ionization detector is the photographic emulsion. Suppose that an alpha particle were to pass through an emulsion. It would ionize many of the atoms along its path. Ionization will, in general, render developable an unexposed silver halide grain. Hence an alpha particle will leave behind it a row of grains which turn black when developed. Similarly, an electron will leave a much thinner trail, i.e., a trail consisting of only a few grains. Photographic emulsions, therefore, may be used not only to detect and count, but also, from track-density, to identify the nature of the particle passing through the emulsion. Neutrons again do not leave tracks; but if the plate is impregnated with some boroniferous compound, the resulting alpha particles are easy to spot. Photons also will affect only one grain, and unless present in great quantity are less suitable for this technique. Ordinary photography, of course, is photon-detection by emulsions, but this is a problem involving billions of photons and so is outside the scope of the present discussion of individual effects. Photographic emulsions are normally in a plane, and hence it is easy to miss tracks which would lie at a large angle with respect to the plane of the emulsion. Location of the tracks may be expedited by projecting the film on a large screen; but the actual track measurements must be done under a microscope and are laborious. Nevertheless, the plate has also its place in detection and is especially useful for slow, heavy particles.

CONTRIBUTORS

Richard P. Feynman went from work on his doctorate thesis at Princeton to a critical position as theoretical physicist at Los Alamos during the war years. With the close of hostilities he went to Cornell where he is now Associate Professor of Physics at the Laboratory of Nuclear Studies.

Serge A. Korff began tracking down cosmic rays as a Research Fellow at CalTech when he headed their 1934–35 expedition to Mexico and Peru. He searched them out in Peru again in 1937 and later at the Mount Evans Laboratory in Colorado. Now Professor of Physics at New York University, Dr. Korff's most recent trip was the January 1948 Puerto Rico expedition of NYU.

Howard A. Robinson started out in academic work as an instructor in physics at Ohio State, with a background of study at MIT and in Germany and Sweden. In 1937 he joined the Armstrong Cork Company, where he is now chief physicist and manager of physical research. He is also Professor of Physics at Franklin and Marshall College where he is giving courses in atomic and molecular spectra.

ABROAD *Continued from page 15*

most striking advances since the end of the war are not those that involve the use of big machines. Especially fruitful have been the studies of cosmic radiation. For cosmic radiation the best-known centre is Professor Blackett's at Manchester and, more recently, Professor Powell's at Bristol. In a field like this, one can still hope to do something—if not with string and sealing wax, at least with quite limited resources. This is shown particularly well by the recent success of Professor Powell and Dr. Occhialini in the discovery of the heavy meson. For a number of years Professor Powell had been developing the photographic plate as an accurate method, comparable with the Wilson chamber, for the determination of the range of charged particles. Given this long and painstaking background, the experiment was simple enough; just to leave some plates on the top of a mountain for three weeks, and then to look through a microscope to see what reaction the cosmic rays had produced. Out of this came the heavy meson, which has gone such a long way to simplify current nuclear theories. An experiment, we feel, in the true Rutherford tradition.

Professor Blackett's school at Manchester specialises in the development of large Wilson chambers for cosmic-ray work; a recent success has been the discovery by Dr. Rochester of a yet heavier form of the meson.

Nuclear physics, of course, is not the only subject under investigation in British universities, though some of our industrial friends may feel we do too much of it, because what they want is young men trained in industrial subjects. Actually, apart from the heavy meson, it is probably true that the most striking advances since the war on this side of the Atlantic have come in other subjects, in the study of the solid state and of low temperature. The next article in this series, therefore, will tell of the researches here on the mechanical properties of metals, which have gone a long way toward turning an obscure technical subject into a respectable part of physics. N. F. MOTT

One of our isotopes, a small boy aged six, recently passed judgment on physics. The bridge of his nose was taking a terrible battering as he tried to retrieve three ice cubes stuck to the bottom of an up-ended glass. "Physics," he said in disgust taking the glass from his face, "this physics! Three ices and all physicked together."