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The Study of Atomic Processes with the Photographic Plate[1]

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Photographic Emulsions for Nuclear Particles

It is well known that a photographic emulsion owes its sensitivity to the fact that radiation by visible light, ultraviolet or gamma rays ionizes atoms in the silver bromide grains. Upon development these will blacken when a certain minimum of ionization has been surpassed. An atomic particle, such as an electron, proton or heavier particle carrying an electric charge, when moving through matter will also ionize the atoms it happens to pass. A photographic emulsion can therefore record the paths of such elementary particles when they move through it. Such a "track" will appear as a row of blackened silver grains which can be seen when viewed under a microscope with suitable optical conditions. In order to make a track distinguishable against the general back-ground of the plate, certain conditions must be fulfilled, and the so-called "Nuclear Research Emulsions", developed in recent years for the specific purpose of recording nuclear events, differ from the ordinary plate, in that they contain about eight times the ordinary amount of silver bromide per cc. and are often some 100 times as thick. The much higher proportion of sensitive matter makes it possible to discern the paths of singly charged particles, even when they travel at such a velocity that their ionization is at the minimum possible rate. The great thickness, which in present experiments may exceed 1 mm, greatly increases the possibility of studying nuclear events in all three dimensions. The photographic plate has certain advantages over the other research tools used in the study of cosmic radiation and other atomic processes: (1) It is continuously sensitive for the time of the exposure; (2) Its effect is cumulative; (3) It is comparatively small, light and cheap. In a few square centimetres hundreds or even thousands of nuclear events may be permanently recorded without overcrowding the plate. The density of the emulsion, and hence its stopping power, is about 2,000 times that of the atmosphere at sea level. An atomic particle entering the emulsion will therefore come to rest in $^1/_{2,000}$ of the time needed in air of atmospheric pressure. This is of great advantage in the study of short-lived processes such as occur in meson events, so that there is a greater chance of their being recorded entirely inside the emulsion. A cloud chamber with the same stopping power would have to have an internal pressure of 2,000 atm. which is at present beyond practical possibilities. A certain drawback of the photographic plate is that no information may be gained about the distribution in time of the recorded events, although with interrelated events it is generally possible to deduce the order in which they occur.

Characteristics of the Recorded Tracks

A charged particle entering the emulsion with a certain velocity loses energy mainly by ionizing the atoms of the surrounding matter along its path. The ionization per unit length depends on the electric charge and on the velocity of the particle, and clearly, will increase with increasing electric charge and decreasing velocity. Heavy atomic nuclei carrying a multiple charge, therefore, leave tracks of a heavy grain density which usually results in a black line without any gaps. The variation of ionization, i. e. grain density, with velocity, is from a minimum at velocities near that of light, increasing to a solid line where the particle is stopped. Given the same initial velocity all particles with the same charge but different masses will show the same grain density to start with, but the length of the track, i. e. "range", depends on the kinetic energy, and the rate of increase of the grain density to its maximum will, therefore, be the more gradual the heavier the particle. The unit charge may be carried by at least six particles with widely

[1] On account of the large number of scientists who have contributed to the development of the photographic method in atomic physics, a reference list would be exceedingly large. We may draw attention, however, to the reading list below, which may act as a guide to those interested in pursuing the subject matter further.

- M. M. Shapiro, *Tracks of Nuclear Particles in Photographic Emulsions*, Rev. Mod. Phys. *13*, 58 (1941).
- C. F. Powell, G. P. S. Occhialini, D. L. Livesey, and L. V. Chelton, *A New Photographic Emulsion for the Detection of Fast Charged Particles*, J. Sci. Instr. *23*, 102 (1946).
- C. F. Powell and G. P. S. Occhialini, *Nuclear Physics in Photographs* (O.V.P., London, 1947).
- H. Yagoda, *Radioactive Measurements with Nuclear Emulsions*. (John Wiley & Sons, New York, 1949).
- R. W. Berriman, *Recording of Charged Particles at Minimum Ionisation in Photographic Emulsions*. Nature *161*, 432, *162*, 992 (1948).
- Communications of the Bristol Group, Phil. Mag., *40* and *41* (1949, 1950).

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varying masses. They are: electrons, μ-mesons, π-mesons, protons, deuterons and tritons, which have, in terms of electron masses m_e

1, 212, 286, 1,837, 3,674, 5,600 m_e respectively.

The rate of increase of ionization of electrons, mesons and protons, and in favourable cases also, of deuterons and tritons, is sufficiently different to provide a criterion for identifying their tracks.

Another noticeable property of a track in the emulsion is the continuous small angle deviation from a straight line which is called scattering. It is caused by the attraction or repulsion of the charged particle by the electric fields of the atoms composing the medium. Again it is evident that the magnitude of these interactions and the frequency with which they occur will increase with decreasing velocity, and be less as the mass of the particle concerned becomes greater. In general, the small angle scattering is more marked than the variation of grain density and in many cases it is possible to identify a track clearly by inspection. In Fig. 1 are shown photomicrographs of the tracks of: (*a*) an alpha particle of mass 7,292 m_e and charge 2; (*b*), a proton of mass 1,837 m_e and charge 1; (*c*) a μ-meson of mass 212 m_e and charge 1; and (*d*), an electron of unit mass and charge. The increase in grain density of the meson and electron tracks towards their ends is seen to be more rapid than that of the heavier proton or alpha particle. The difference of the small angle scattering is, however, more marked.

The combination of grain density measurement and that of the scattering permits the determination of the mass and energy of the particle concerned, even if its track does not end in the emulsion. The main conditions are that a sufficient length of a few mm should be available, and that the region of the plate is free from distortion and evenly developed in depth. This method is particularly suitable for particle energies up to 20,000 MeV, which are not rare in the cosmic radiation.

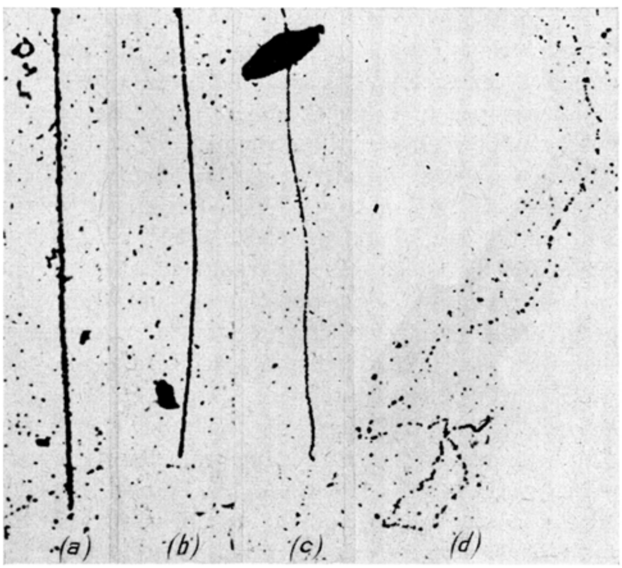

Fig. 1. – Typical tracks of (*a*), an alpha particle, (*b*), a proton, (*c*), a μ-meson and (*d*), an electron in a nuclear research emulsion.

The modern nuclear research emulsions are thus not only a means of recording nuclear events, but are also an instrument for quantitative measurements of the greatest value. A major problem in using them lies in the processing of the thick emulsions. A considerable time is required for aqueous solutions to penetrate to the glass interface through the gelatine-silver bromide matrix. For instance, a developer solution diffused into the plate at ordinary temperatures will act on the surface layers for a much greater time than on those lower down, so that the grain density of a dipping track will appear higher at the surface than near the glass. In order to overcome this difficulty, the "temperature cycle" method has been introduced. The plate, first cooled and soaked in water at 5° C, is transferred to a bath of developer at the same temperature and left there for a time sufficient to allow complete penetration of the solution to the bottom of the emulsion. This is achieved without appreciable development taking place because the reduction in chemical activity is much greater than that of physical diffusion. The temperature of bath and plate is then raised slowly so that development can proceed, and continues for perhaps half an hour or more dependent on the agents employed and their concentration. Sometimes it is desirable to isolate the plate from further contact with the solution throughout this stage.

Further development is avoided by returning the plate to a 5° C bath and then applying a chemical stopping solution in the cold. Fixation is necessarily a long process requiring many changes of the hypo-solution and must be carried out carefully in order to avoid distortion of the gelatine through the great reduction in volume at this stage. When the plate has cleared completely, a gentle wash in cold water for several hours is applied. In the drying stage, the emulsions must be kept horizontal in an atmosphere of rather high humidity in order to avoid stresses at the edge and surface. The total time required for the processing of an emulsion 600 μ thick may exceed 96 hours, during which it must be constantly attended.

The Cosmic Radiation

In the study of natural radioactivity with sensitive instruments, a certain background ionization effect was observed. The intensity, however, was found to increase as measurements were made at higher altitudes, and it was therefore concluded that a natural radioactivity of the earth or the atmosphere could not be the cause.

It is now finally established that this ionization is due to a stream of highly energetic nuclear particles. This cosmic radiation coming from outer space with velocities near that of light, strikes the top of the atmosphere. The origin of these particles, and the manner in which they receive such great accelerations is still a subject of speculation.

These particles originate a chain of nuclear reactions in the depth of the atmosphere and are eventually absorbed. The secondary and tertiary effects include all types of nuclear interactions and others which, so far, have only been observed at the high energies at which degeneration of the cosmic radiation takes place. A great many secondary particles are accelerated in these processes to such high energies that they are capable of penetrating down to sea level, and sometimes great distances into the earth.

On account of the increased cosmic ray intensity observed at greater heights it was only logical that measurements at mountain altitudes should be attempted. The new photographic emulsions are of great value in this research as they are simple and light. In order to obtain information concerning the energetic processes by which the cosmic radiation disperses its energy in the atmosphere, packets of these plates have therefore been placed on the Pic du Midi (2,800 m), on the Jungfraujoch (3,500 m), on Mount Kilimanjaro (4,800 m), and in the Andes (at 5,000 m) for periods up to six weeks. Charged particles incident on the emulsion of the plates will penetrate the matrix of silver bromide crystals and gelatine, and will upon development appear as the characteristic tracks described earlier. Occasionally, a fast particle will collide with the nucleus of one of the atoms contained in the emulsion and break it up into fragments which are projected in all directions. The charged fragments, which may be mesons, protons or heavier particles, divide between them the charge of the original nucleus, and their tracks in the developed plate are seen to radiate from the point of disintegration. Such an event is called a "star" and a great many of these are observed, some with a large number of prongs and some with only three or four, depending on the energy of the particle which caused the explosion and the weight of the struck nucleus. Neutrons are also projected in such an evaporation of a nucleus, but, unfortunately, the photographic emulsion is unable to record their paths as their ionizing power is too weak. Typical stars are shown in Fig. 2.

At altitudes of only a few thousand metres the radiation has already passed through a great thickness of air with consequent considerable reduction by absorption. From a detailed study of large numbers of stars, it is found that the most energetic ones are produced by particles travelling in directions close to the vertical, having penetrated a minimum distance through the atmosphere. It was soon suspected that the majority of the energetic particles observed to be incident on the plates at mountain altitudes, were secondary products of processes occurring much higher in the atmosphere, and that, in order to obtain more information of the primary cosmic radiation it would be necessary to make exposures at altitudes of 30,000 m or more, where the atmospheric pressure falls below 1 cm of mercury.

By the use of free balloons filled with hydrogen, cosmic ray apparatus may be carried to great heights, and kept there for periods of several hours, which would be equivalent for integrated intensity to weeks at the Jungfraujoch altitude. It is obvious that the photographic plate is the most convenient instrument to use in this type of experiment, as it will preserve in a small area the latent images of a large number of events. It is only necessary to carry the plates thermally insulated in order to prevent the effects of desensitization at low temperatures.

The problems of attaining a level flight at a height of, say, 30,000 m may be attacked in different ways.

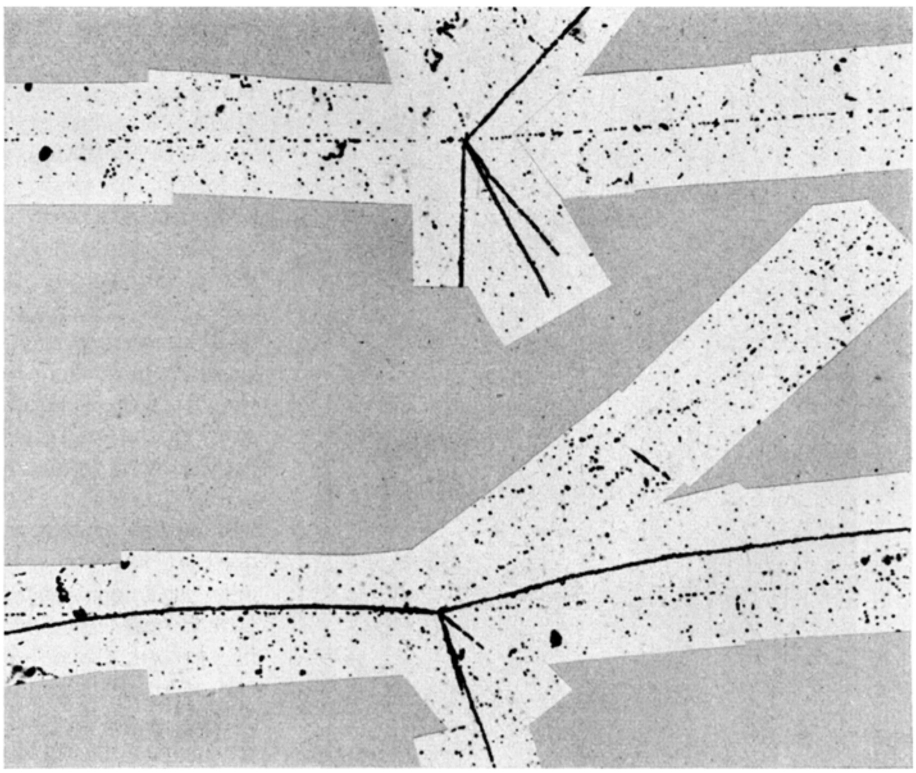

Fig. 2. – Cosmic ray "stars".

Two types of balloons have been proved to be useful, one of thin rubber, constructed similarly to those used in meteorology, and the other fabricated from a thin non-elastic polyethylene material. The rubber balloons are filled with hydrogen until a certain lift is achieved, and then corked. While ascending, the rubber fabric stretches until the diameter is about five times the original, when the balloon bursts. On the other hand, the balloons of plastic material have a large initial volume which is only partially filled at ground level. In ascent, the enclosed gas expands and will eventually extend the balloon to its full volume. Any surplus hydrogen is ejected through an inverted tube until equilibrium is realized between lifting power and load. The ratio between the volume of hydrogen needed at sea level to lift the load, and the total volume of the fully extended balloon, directly determines the altitude it will reach. These balloons are not designed to withstand any internal pressure.

In both cases, the load consisits of a gondola which carries the plates in their packing, and a height-recording instrument. The latter is a small aneroid barometer which is arranged to vary the signal frequency of a tiny short-wave transmitter. Information

Fig. 3. – A small experimental balloon of plastic material.

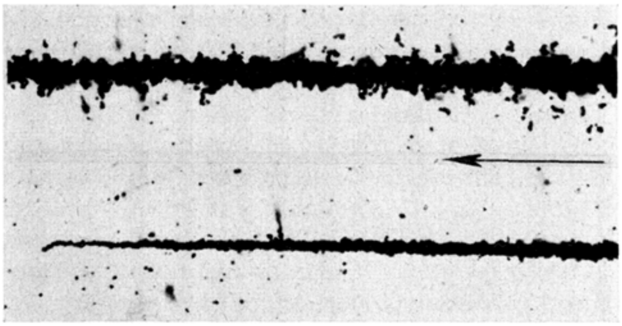

Fig. 4. – The track of an energetic iron nucleus which came to rest in a plate carried to 30,000 m by free balloons.

of the altitude attained and the approximate position is thus available continuously on the ground.

In order to obtain a level flight at high altitudes with rubber balloons, it is necessary to use more than one, because the lift of a single balloon remains almost constant, so that it will rise until it bursts. A cluster of three is therefore assembled and filled so that any two will just support the weight of the gondola. This arrangement rises until one of the three bursts. The two remaining will carry the equipment in level flight until a second one bursts, when the load returns to earth supported by the third. However, the balloons behave in a most unpredictable manner when expanded to near their bursting diameter, and there have been anxious moments for those responsible when both second and third balloons exploded together. In flights with heavier and more elaborate equipment in which the effect of lead absorbers are studied, a greater number of balloons is used. In order to maintain the maximum lift, the debris of any balloon which bursts is jettisoned by means of a mechanical release device. Nevertheless, level flights are difficult to obtain with arrays of this type.

The plastic balloons are fabricated from shaped pieces of maximum width of about 1 m, heat-sealed together along their edges. They consist therefore of many sections, and a certain leakage of hydrogen is inavoidable. Such a structure designed to carry a load of 10 kg to a height of 30,000 m has a diameter of more than 20 m and a length of nearly 35 m. The dead weight of the skin amounts to about 50 kg. Leakage through the seams of the large area involved may be compensated by the release of sand ballast through a mechanism which is brought into operation when the balloon has reached its maximum height. This can be done either by means of a sensitive aneroid barometer or by radio control from the ground. Reports from the U.S.A. indicate that high altitude level flights of many hours have been obtained in this way. At the end of a predetermined time of flight, the gondola is cut off from the balloon and returns to the ground supported by a parachute. Fig. 3 shows a small experimental polyethylene balloon constructed at Bristol in order to gain experience with type of flight.

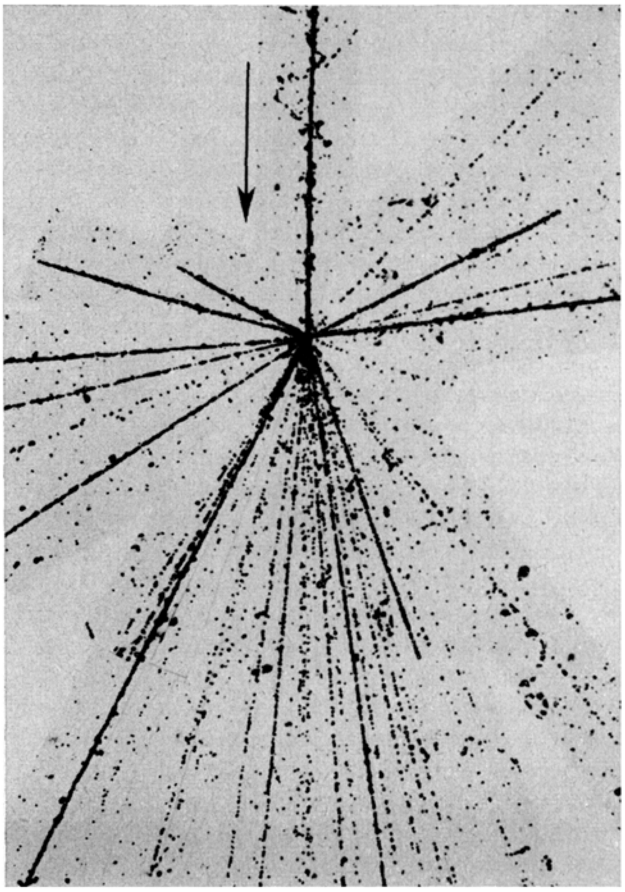

Fig. 5. – A nuclear explosion of high energy, produced by a fast nuclear fragment of Z $\geqslant$ 20.

The characteristics of the observations at 30,000 m are considerably different from those at mountain altitudes. Energetic atomic nuclei with multiple charge are only observed above 25,000 m as they suffer rapid absorption in the thin air. An example of the track produced in the emulsion by one of these particles is shown in Fig. 4, and it can be seen that the ionization is much heavier than that of singly charged particles. In addition, the tracks are surrounded by a great number of short-range electron tracks called delta rays originating on the main-track. It is known that the number per unit length of these tracks increases as the square of the charge carried by the nuclear fragment, and we may therefore determine this quantity and hence the mass. In general it has been found that the distribution of the masses of these particles is in good agreement with the known relative abundances of the elements in stellar matter, and therefore there is good reason to suppose that these heavy fragments represent the primary radiation coming from outer space.

In the same manner as described for mountain altitudes, stars are produced in the emulsion, and occasionally one is observed to be caused by a collision of one of these heavy particles. The collimation with respect to the vertical direction of the star-producing radiation is much less pronounced in the stratosphere exposures, which is in good agreement with the supposition that we are dealing with a radiation closely related to the primary. The average energy of the disintegrations is also much higher in these exposures.

High Energy Transmutations of Atomic Nuclei

The energy with which a particle is projected may be expressed in terms of electron-volts (eV). This means that it moves with the velocity which it would acquire if it were accelerated in an electric field whose potential difference is this voltage. A 1-million-volt potential therefore, acting on a singly charged particle, will give it a kinetic energy of 1 MeV, and a particle carrying Q electric charges, Q_{MeV}.

Particles are ejected from nuclear stars with energies ranging from a few MeV up to several thousand. It is clear that a particle producing a star must carry an energy equal to the sum of all the energies of the disintegration products, including those of neutral particles whose tracks are not visible. Transmutations have been found involving an energy exchange of up to 500,000 MeV, equivalent to about $^1/_3$ erg, in a single star. Fig. 5 is an example of such a spectacular event.

The majority of stars show the comparatively low energy exchange of a few hundred MeV. In about half

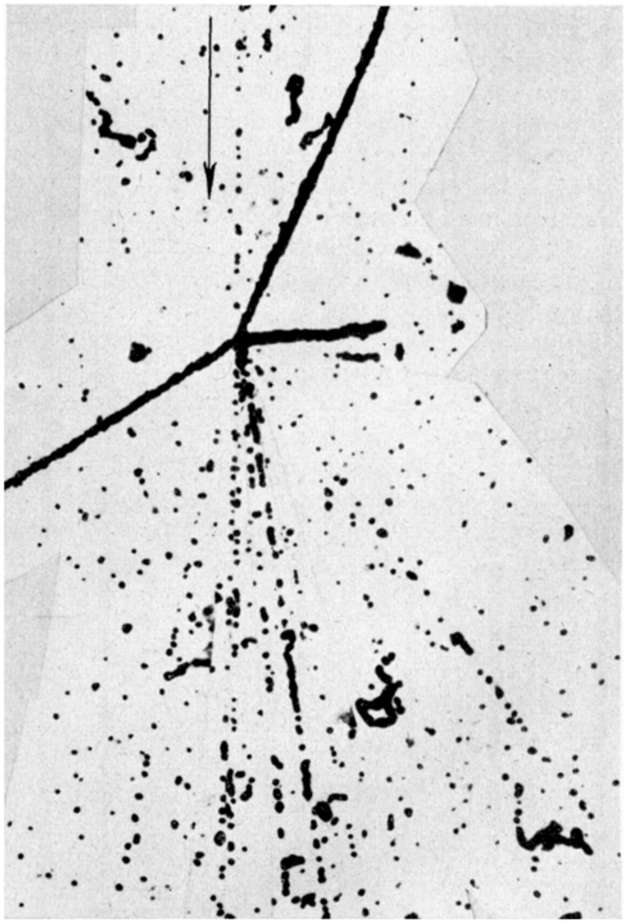

Fig. 6. – A meson shower.

the cases there is evidence that one of the tracks is that of an incoming particle, usually of single charge. It is reasonable to assume that the majority of these incident particles are protons, but some have been identified as mesons. The remainder are the result of collisions by neutrons, and possibly a few by photons, i. e. electromagnetic waves, of high energy.

Incident particles of energy greater than 1,000 MeV tend to interact with the individual components of an atomic nucleus (nucleons), rather than with the atom as a whole, resulting in the emergence of a process of a different type. The nucleons are held together by the strong "meson forces". Violent impact results in the disruption of these binding forces, which appear as separate particles called mesons, possessing a definite rest mass but very short half life. One or more mesons per nucleon may be created in this way, and their directions of ejection are grouped predominantly about the direction defined by the incoming particle, forming a cone of tracks which is known as a "meson shower". The mesons emitted in the forward direction are usually of high energy and thus form tracks of minimum ionization. This gives the event a characteristic appearance of which Fig. 6 is an example. Some of the mesons are also emitted backwards, and, to a smaller extent, sideways. The generation of mesons is generally accompanied by the disintegration of the struck nucleus in the same manner as with ordinary stars, and the presence of tracks of intermediate grain density indicates that some fragments receive considerable energy. In these shower stars the major part of the incoming energy is carried away by the shower particles, an appreciable fraction being transformed into meson rest masses. The mass of the shower particles has been determined as about 286 times that of the electron, a value coincident with that of the π-mesons. It can therefore be assumed that the slow positive and negative π-mesons observed earlier originate in shower processes.

The particles are unstable and have a lifetime of only about 10^{-8} sec. If a positive π-meson comes to rest in the emulsion its decay into another charged meson of about 212 electron masses can be observed. The kinetic energy with which this meson is projected has a constant value of about 4·2 MeV, which results in a constant track length of about 580 microns in the plate. The lifetime of this secondary particle, called a μ-meson, is about $2\cdot10^{-6}$ sec. and we believe that it is extremely unlikely to interact with nuclei. At the end of its lifetime, which is generally after the new particle has come to rest, a spontaneous decay takes place in which the only observable track is that of an electron of variable energy. In order to provide a momentum balance in this process, it is necessary to consider the simultaneous emission of at least two neutral particles.

The negative π-mesons may also follow this decay chain, especially in light elements, but on slowing down in the material of higher density, such as the emulsion a competing process is far more likely to occur. This is the capture of the negative π-particle by a positively charged nucleus. The decay energy of the captured particle appears as excitation of the nucleus, resulting in its partial or complete disintegration. π-mesons of both signs ejected from stars have been found to come to rest in the emulsion, thus telling in one plate the complete life cycle of the meson. The great majority of these events are of π^--particles because of the relative ease with which they can leave the parent nucleus with the low energy necessary to remain in one plate. A picture of an ejected π-particle which causes a secondary disintegration is shown in Fig. 7. It may be pointed out that no other method of investigation enables this process to be examined in its completeness.

Gamma Radiation and Electron Cascades

The cosmic radiation gives rise to extensive cascades of fast electrons and associated gamma ray quanta, or photons, in the atmosphere, and because these showers are rapidly absorbed in solid material they are known as the soft component. The photographic plate has proved a valuable research tool in the experimental study of the multiplication effects of gamma rays and electrons at high energies. The method has a unique advantage that the ionizing components of these showers leave tracks in an almost transparent material of high density, and the individual steps which, in the plate follow one another so quickly, may be studied in their mutual relation. The cascade process, as is well known, is initiated by either an energetic photon or

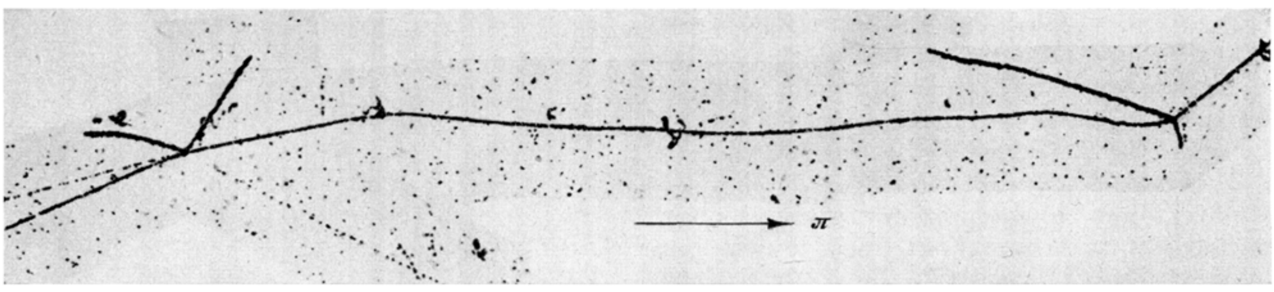

Fig. 7. – An example of the emission of a π^--particle in a nuclear explosion and its subsequent capture by another nucleus, causing a secondary disintegration.

electron. The probability with which a photon is transformed into a pair of electrons of opposite charge is fairly high, increasing rapidly in materials of high atomic weight. A photo-mosaic of a pair production event in the emulsion is shown in Fig. 8. A fast electron, on the other hand, has a similar likelihood of losing a large fraction of its kinetic energy in the form of an emitted quantum. This radiation loss process is called "Bremsstrahlung". The photons created in such a way will, in turn, transform into pairs of electrons which suffer further radiation losses, and the multiplication of photons and electrons continues until the initial energy has been so far dissipated that the cascade comes to a stop. It may be mentioned here that 5 cm of lead is sufficient to absorb the majority of the soft component at sea level.

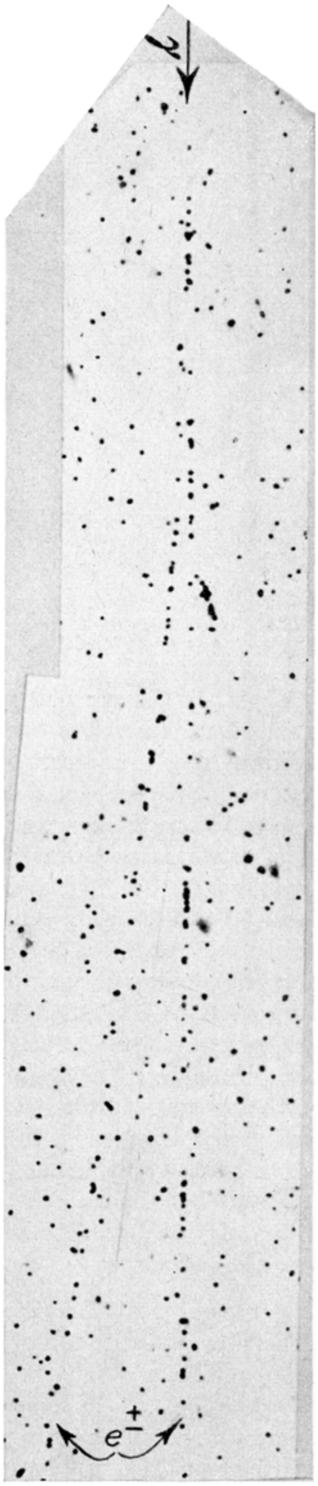

Fig. 8. – Electron-positron pair production in a nuclear research emulsion.

At high photon energies the two tracks of an electron pair event travel closely together for a considerable distance, but at medium and low energies they have an initial angular separation of a few degrees. Under suitable conditions, when both tracks have a sufficient path length in the emulsion, a determination of the small angle multiple scattering on each track gives the energy of the created particles, and hence that of the gamma ray. A considerable disparity in the energies with which the two particles are projected is frequently noted. In exposures on balloon flights at 22,000 m a spread of quantum energies extending to more than 20,000 MeV has been observed.

Positron-electron events are found to originate not only by gamma ray transformations, but also on the tracks of fast particles. Events of this type are called Tridents. In such a process the electric field of the incident particle interacts with the Coulomb field of a nucleus near which it passes. It is known that the majority of these primary particles are electrons. The disturbance of the fields is of such a nature that an electron pair is formed, either directly, or by an intermediate photon of extremely short life. The highest optical resolution fails to indicate any displacement of the pair origin from the track of the electron producing such an event. The probability with which a fast electron creates a trident depends markedly on its energy, increasing rapidly above 1,000 MeV. Nevertheless, it is of such a magnitude as to make only a small contribution to the electron cascade showers of the cosmic rays.

The origin of the energetic electrons or photons producing the soft showers has been a subject of speculation for some years. Two arguments are relevant in this matter. Firstly, it is apparent that fast electrons are not emitted in nuclear disintegrations, and secondly, that balloon flights with ionization chambers early indicated that the soft component was generated

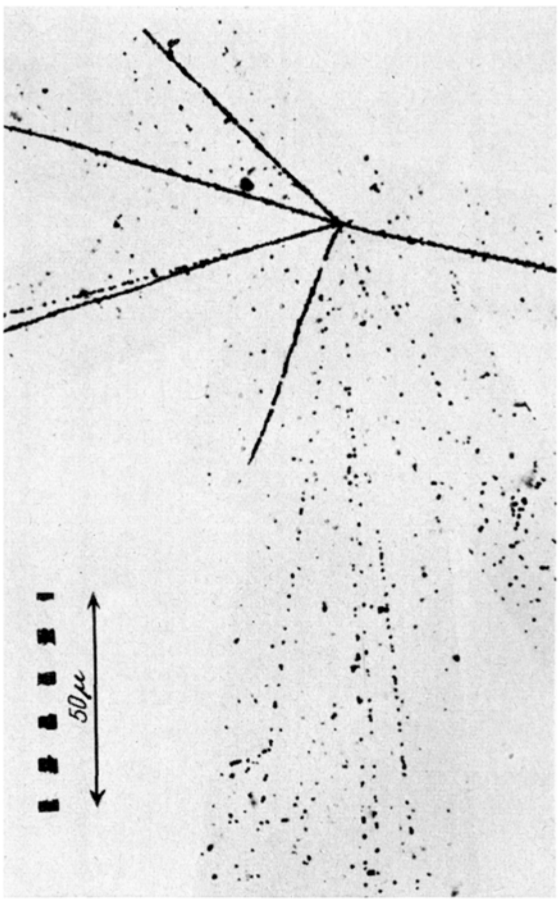

Fig. 9. – A meson shower with which an electron pair production event is associated.

locally in the atmosphere at a height of about 25,000 m. This leaves a possibility that energetic photons are emitted in nuclear disintegrations produced by the cosmic ray primaries. Recent observations in the U.S.A. and in this country seem to indicate that this is indeed the case. In several meson shower events, electron pairs have been found orientated in such a way as to suggest that the producing photon originated in or near the disintegration. An example of a meson shower with which a gamma ray pair is associated is shown in Fig. 9. As it is, however, unlikely that photons of several thousand MeV are generated directly in nuclear explosions, an interesting but so far rather tentative suggestion to explain these observation has been advanced. Neutral mesons, long required by nuclear theory, may be ejected together with the charged π-particles in the meson shower processes, and perhaps decay spontaneously with a very short half life into two or more gamma rays. The latter would transform into electron pairs and thus originate, in agreement with our observations, the soft component.

Geological Uses of the Nuclear Research Emulsions

Parallel with the development of the photographic method in the study of the cosmic radiation went its application to other fields involving atomic processes. The weak natural alpha radioactivity of certain minerals is conveniently detected and measured with emulsions sensitive to alpha particles, particularly where the location of the emitting material in the geological structure is of interest. A polished section of the rock is placed in contact with the emulsion and left there for periods of up to several weeks. Microscopic examination reveals groups of alpha particle tracks which are seen entering the emulsion from the surface. An example from a specimen of coal is shown in Fig. 10. A more accurate knowledge of the intensity is obtained if the material is first powdered or converted into a solution which is allowed to diffuse into the emulsion. In the latter case the stars of successively emitted alpha particles are seen throughout the depth of the plate. Sometimes, length measurements on the tracks coming from the stars reveal the nature of the radioactive nucleus present, providing valuable clues about the evolution of the mineral.

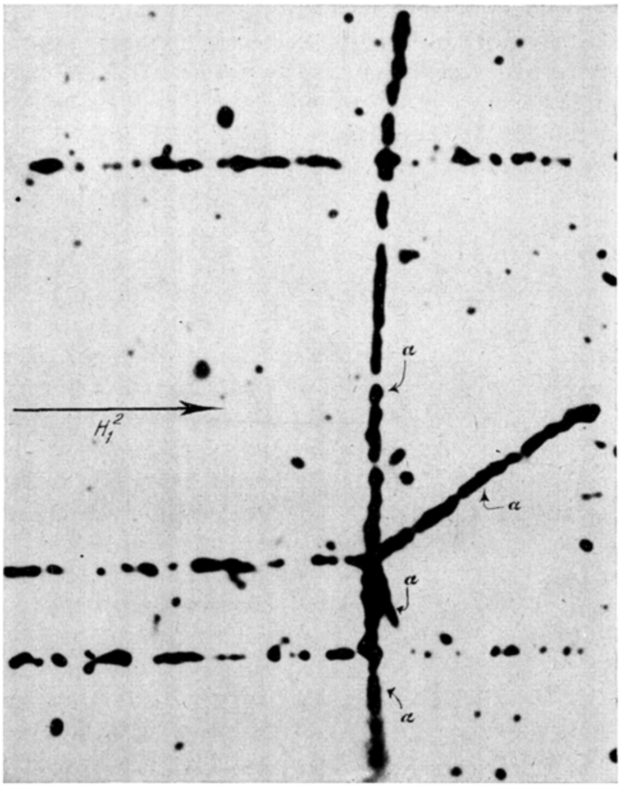

Fig. 11. – A 9-MeV deuteron collides with a nucleus of nitrogen in the emulsion and the resultant nucleus dissociates into four alpha particles.

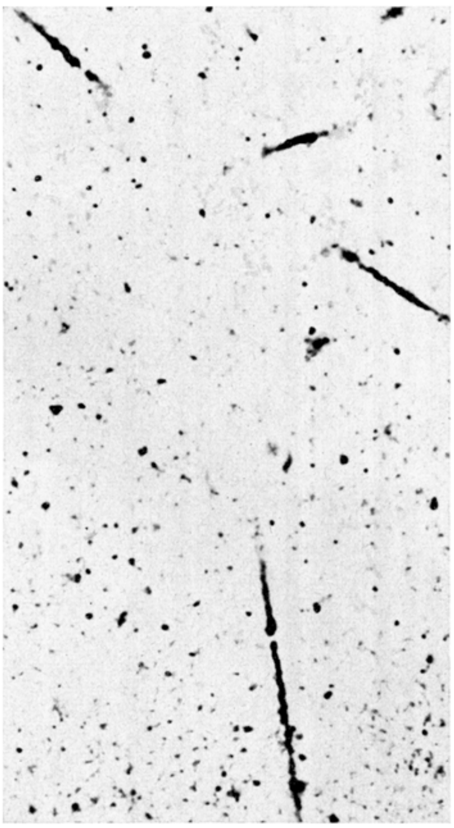

Fig. 10. – Alpha particles from a grain of coal dust.

Gamma Ray Spectroscopy

Atomic nuclei may also be broken up under the action of energetic photons. This process, called photo-disintegration, may be used to measure gamma ray energies in the region of 10–100 MeV, such as is available from present day betatrons and synchrotons. The energy of a photon causing e.g. the splitting of a carbon nucleus into three alpha particles may be determined by addirg the energies of the three coplanar alpha tracks, a correction being made for

Fig. 12. – The tracks of alpha particles in a boron-loaded plate which had been exposed to a beam of slow neutrons.

the binding energy of the carbon nucleus. The ejection of protons from deuterium nuclei loaded into the emulsion is another method. Owing to the low probabilities for photo-disintegration processes, however, they are unsuitable for studying the low-intensity gamma ray fluxes of the cosmic radiation.

Nuclear Transformations at Low Energies

Modern atomic particle accelerators such as the Van der Graaf machine or cyclotrons and their modifications, produce beams of protons, deuterons or alpha particles of nearly homogeneous energy. These are directed against a target of a chosen element. The interactions between the bombarding particles and the target nuclei are of varied types, and provide information regarding the structure of nuclei. The incident nucleus may be scattered elastically, leaving the struck nucleus in an unchanged state. If inelastic scattering takes place, energy, nucleons, or both, are exchanged. Whatever the type of the interaction, some of the products of the atomic collisions are detected in an emulsion placed near the target, and from variations in the relative directions and densities of the tracks in different parts of the plate, it is possible to deduce something of the forces acting between nucleons. In some experiments it is convenient to bombard the plate directly, so that the atomic nuclei of the emulsion act as the target. Fig. 11 illustrates three tracks from a parallel beam of 9 MeV deuterons, incident at a small glancing angle to the plane of the emulsion. One of these particles strikes a nucleus of nitrogen and the resulting inelastic collision is represented by

$$H_1^2 + N_7^{14} \longrightarrow O_8^{16*} \longrightarrow 4\,He_2^4.$$

The nucleus of oxygen is formed in a highly excited state and dissociates almost immediately into four alpha particles. These form short tracks of high grain density which radiate as a star from the point of interaction.

Alpha Tracks Radiography

If boron or lithium are irradiated with slow neutrons, there is a high probability per atom that an energetic reaction will occur. This process, known as thermal neutron capture, is represented in the case of boron by the equation

$$B_5^{10} + n_1^0 \longrightarrow Li_3^7 + He_2^4,$$

the alpha particle, being projected with an energy of more than 1 MeV, may be recorded in a photographic plate. In this way traces of boron or lithium may be detected and measured in matter when it is exposed to concentrated beams of thermal neutrons, such as are available in the uranium pile. In biological experiments, thin sections of the specimen are placed in contact with the emulsion surface, then wrapped in black paper and sent for exposure in the pile. On account of the high neutron fluxes employed and the consequent heavy gamma-ray backgrounds, it is necessary to use plates sensitive only to alpha particles, to avoid fogging. The subsequent processing of the emulsion, lasting several hours, must be carried out with the dewaxed specimen in position, a problem which still requires satisfactory solution. To illustrate a further difficulty

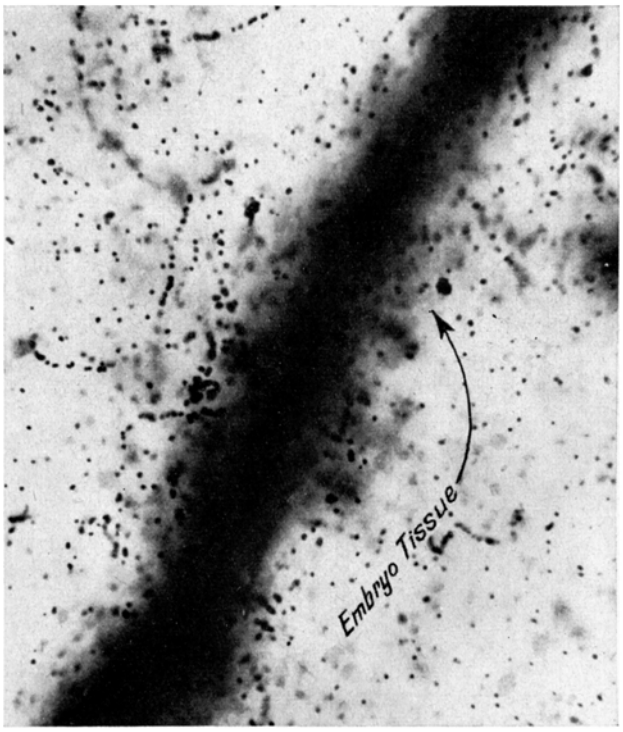

Fig. 13. – Tracks of beta particles in a "nuclear research" emulsion with which a section of embryo treated with phosphorus-32 is in contact.

with regard to specimens containing highly soluble lithium compounds, all stages of preparation and flotation up to the time of exposure must be carried out in the absence of water or alcohol.

In order to monitor the integrated thermal neutron flux of each exposure, boron or lithium-loaded plates are incorporated with the irradiated packets. Fig. 12 illustrates the characteristic tracks of alpha particles from boron obtained in one of these control exposures.

Electron Track Radiography

Experiments in which the photographic location and estimation of small quantities of radioactive isotopes are studied in sections of biological materials, have recently become of interest. Thick emulsions capable of recording tracks of electrons at minimum ionization may be used in this type of work, if observations are restricted to those tracks entering the exposed surface. The difficulties mentioned in the preceding section with regard to processing and soluble materials apply here also. Tracks from a section of an embryo treated with phosphorus-32 are shown in Fig. 13.

It is possible, by making an extremely intimate contact between the histological specimen and the emulsion, to infer the starting point of an electron track within an accuracy of a few microns. The high sensitivity of the method enables the amount of isotope used to be reduced to a fraction of a microcurie, and exposure times down to hours instead of weeks. Those isotopes of short half-life therefore become available for these experiments. It is preferable to use pure beta emitters with no gamma radiation which might produce confusing electron tracks in the neighbourhood of the specimen. It is necessary to point out that electron sensitive plates rapidly become useless for this work if placed in storage for periods longer than a few days, as they accumulate tracks of slow electrons produced by the soft component of the cosmic radiation. An alternative to the use of freshly manufactured plates is the employment of stored plates from which the accumulated latent image has been removed by means of a controlled cycle of humidity changes. In this process, however, the restoration to their full sensitivity is rather uncertain.

Conclusion

This brief survey will indicate that in atomic physics the use of Nuclear Research Emulsions is still in its infancy. At first, the photographic plate was used merely as a means of detecting the presence of charged particles, but gradually it proved also to be a measuring instrument. In view of the short period during which rapid improvements have been made in the method, one may reasonably expect the technique to be further perfected as a means of precise measurement in coming years. In this connection, mention should be made of the need for reducing the time and labour of processing emulsions thicker than 1 mm, the introduction of standardized methods in manufacture, and the limitation of distortion effects. We may also expect a noticeably increased discrimination of minimum ionization tracks relative to the backgrounds of spontaneously developed grains. Optical firms are at present engaged in the development of microscopes specially designed for the examination and measurement of atomic particle tracks. This involves the evolution not only of suitable optical systems of high resolving power, but also of microscope stages capable of movements and rotations of the highest precision.

Zusammenfassung

Die Verwendung spezieller photographischer Platten in der Atomforschung wird in Kürze beschrieben. Elektrisch geladene Elementarteilchen, die durch die Emulsion gehen, hinterlassen Spuren, die in der entwickelten Platte unter dem Mikroskop studiert werden können. Die Natur der Spuren und die Methoden, mittels welcher die Teilchen, die die Spuren verursacht haben, identifiziert werden können, werden erörtert. Ein kurzer Überblick über die Höhenstrahlenforschung und ihre Ergebnisse wird gegeben und die bedeutende Rolle, die dieses neue Forschungsinstrument spielt, erklärt. Die neuen Emulsionen finden auch eine immer ausgedehntere Anwendung als Detektor und Meßinstrument in vielen Experimenten, in welchen es sich um geladene atomare Teilchen handelt. Einige wenige davon werden beschrieben.