

The Particle Detectors

I. Nuclear Emulsions

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This is the first of a series of articles which will describe the various types of particle detectors in use around high energy accelerators — how they work, something of their history, their present role and their possible future. The detectors have been divided into four groups: nuclear emulsions, counters, spark chambers and bubble chambers.

The nuclear-emulsion technique was very prominent about 20 years ago. The heyday is now over and the emphasis has moved to fewer, more specialized and complex experiments. This article follows the development of the technique and selects in particular one recent experiment at CERN to illustrate the use of nuclear emulsions in research.

History

The possibility of detecting *individual* charged particles by means of a photographic emulsion was first investigated as long ago as 1910 by Kinoshita, working at Manchester University. He was continuing some earlier work by Lord Rutherford in the same field. Kinoshita showed that a single α particle was capable of rendering a silver-halide grain developable. A year later, Reinganum showed that the passage of an α particle at glancing incidence to a photographic emulsion produced, when the emulsion was developed, a row of silver grains outlining the trajectory of the particle.

This early work was carried out with the type of emulsion used for conventional photography, which had a thickness of only a few microns. It was not until around 1930 that thick-layered emulsions (about 50 microns) were produced, first in research laboratories and later (1935-1937) on a commercial scale by Ilford Ltd in England. These emulsions were exposed for some months at mountain altitudes, for example by Blau and Wambacher, and on subsequent examination 'stars' were found which were ascribed to the disintegration of nuclei in the emulsion caused by cosmic rays.

By 1939, the technique was recognized as a useful tool for the investigation of nuclear and cosmic-ray phenomena, but it was considered

to be only a qualitative method and of limited application. The systematic investigations of Powell from 1940 onwards showed, however, that the method was capable of giving accurate quantitative results. For example, Chadwick, May, Pickavance and Powell studied in great detail the scattering in various gases of particles accelerated in a cyclotron. At the end of the war, Ilford produced a concentrated 'nuclear-research' emulsion containing eight times the normal amount of silver bromide per unit volume. It was in emulsions of this type exposed to cosmic rays at mountain altitudes that the pion was discovered by Powell and his colleagues in 1947.

Finally, in 1947-48, first Kodak Ltd and then Ilford produced an emulsion capable of recording the tracks of particles moving with velocities such that they suffer the minimum possible energy loss (causing minimum ionization) in passing through the emulsion. Such emulsions are commonly known as 'electron-sensitive emulsions'; they can be purchased, if required, with thicknesses as great as 2 mm on glass or 1.2 mm as stripped emulsion, and in sizes up to 40 cm x 40 cm, or greater.

Advantages and disadvantages

Nuclear emulsion possesses one most significant advantage over all other techniques. It is capable of extraordinarily high spatial resolution. Other techniques can resolve



Figure 1. An example of a 'jet' of secondary particles seen in nuclear emulsion following a collision involving a cosmic-ray particle of very high energy. In this case, observed by Daniel, Davies, Mulvey and Perkins in 1952, the particle had an estimated energy of 600 GeV. (The three emulsion photographs reproduced in this article are taken, with acknowledgement to Pergamon Press, from 'The Study of Elementary Particles by the Photographic Method' by Powell, Fowler and Perkins.)

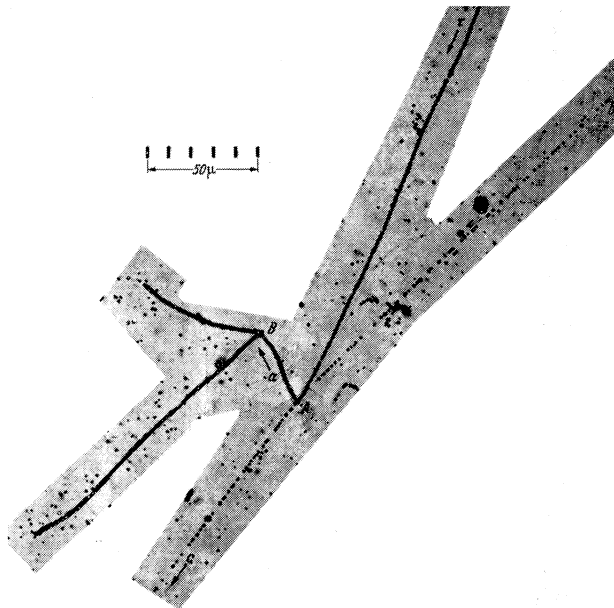


Figure 2. The famous observation of the τ meson in nuclear emulsion exposed to cosmic rays. This was the first clear indication of the existence of the many heavy mesons which have now been identified. The experiment used electron sensitive emulsion, which had just been produced, and was carried out by Brown, Camerini, Fowler, Muirhead, Powell and Ritson in 1948. The τ enters the emulsion from the top of the photograph; b and c are π^+ mesons; a is a π^- meson which gives rise to a star at B.

events separated by a few millimetres; using emulsion we can resolve events separated by a few microns. This has made possible the measurement of the lifetime of the π^0 meson (about 10^{-16} s) and is the basis of our confidence that there are no other commonly occurring unstable particles with lifetimes in the range 10^{-11} to 10^{-16} s.

There are some further advantages which are particularly significant in the case of complex experiments in which nuclear emulsion is used as a detector. First of all, it is an integrating device which can be exposed or irradiated until sufficient data have been stored in it; secondly, it can be used in very confined volumes, as will be illustrated later in this article in the discussion of the experiment to determine the magnetic moment of the Λ^0 hyperon.

Its chief disadvantage is that it consists of a mixture of complex nuclei — silver and bromine (as silver bromide) suspended in gelatine, which is largely carbon, nitrogen and oxygen. Further, the scanning of large volumes of emulsion, of necessity in three dimensions, is frequently very tedious. Thus, with the development of other powerful detectors such as the spark chamber and the bubble chamber (with its simple target material of hydrogen or deuterium for example) which are readily adaptable to automatic methods of analysis and data handling, nuclear-emulsion work has inevitably developed into a supplementary technique, except in certain special fields.

Use of the technique in research

There are two distinct ways in which nuclear emulsions can be used. Firstly, they may be placed in the path of particles (from an accelerator or in the cosmic radiation) and the interactions which these particles produce in the emulsion can be studied in detail. The charged pions and many of the 'strange particles' were first discovered, and their decay modes

studied, in large stacks of emulsion exposed for considerable periods of time to the cosmic radiation (see Figure 2). The relatively small size and weight of emulsions enable them to be carried to great heights by means of free balloons. In this way, many studies have been carried out of

- a) the interactions of very energetic particles — energies greater than 50 GeV (see Figure 1),
- b) the composition of the primary cosmic radiation and
- c) the development of the electron-photon cascade in the high atmosphere.

One well-known example is the work carried out by groups all over the world on emulsions which were exposed on a high-altitude balloon flight as a very large stack (60 x 45 x 30 cm) known as the 'Schein stack' after the American physicist who initiated the project.

The second way in which emulsion may be used is simply for particle detection, placed near to a target which is bombarded by a suitable particle beam. The target employed is often liquid hydrogen, although at cyclotron energies targets of many solids and gases have been used. In many cases the geometry of the experimental arrangement is so designed that the particles we wish to investigate stop in the emulsion, thus allowing their energy to be determined by measuring the distance they travel in the emulsion.

Experiments at CERN

The Emulsion Experiments Committee was first set up in January 1959 to plan and co-ordinate emulsion work at the PS and SC machines. During the first few years of operation of the PS (about 1960-1963), the majority of the experiments were of the first type described above — large blocks of emulsion were placed into particle beams of various types and energies. The stacks were subsequently divided and distributed to emulsion groups in the Member States and elsewhere. The number of groups involved during these years was of the order of 40, of which about 25 were in Member States.

In Europe, two groups of collaborating Laboratories have been active for some years. One, called 'the European K-Collaboration', is composed of two emulsion groups in Dublin, two in London, one in Brussels, two in Prague and one in Warsaw, together with some members of the CERN group. As the name implies, these workers have used K^- mesons of various energies up to 6 GeV to study hyperfragments. (Hyperfragments are nuclear fragments which contain a trapped Λ^0 particle. Since this particle is unstable it eventually decays causing the break-up of the fragment.) Apart from the very large amount of detailed information which has been collected about hyperfragments, the most striking single observation was that of a double hyperfragment, that is, a nuclear fragment containing two trapped Λ^0 particles. This was found by the Warsaw group in 1963, ten years after the first discovery of a single hyperfragment, also by the Warsaw group (see Figure 3).

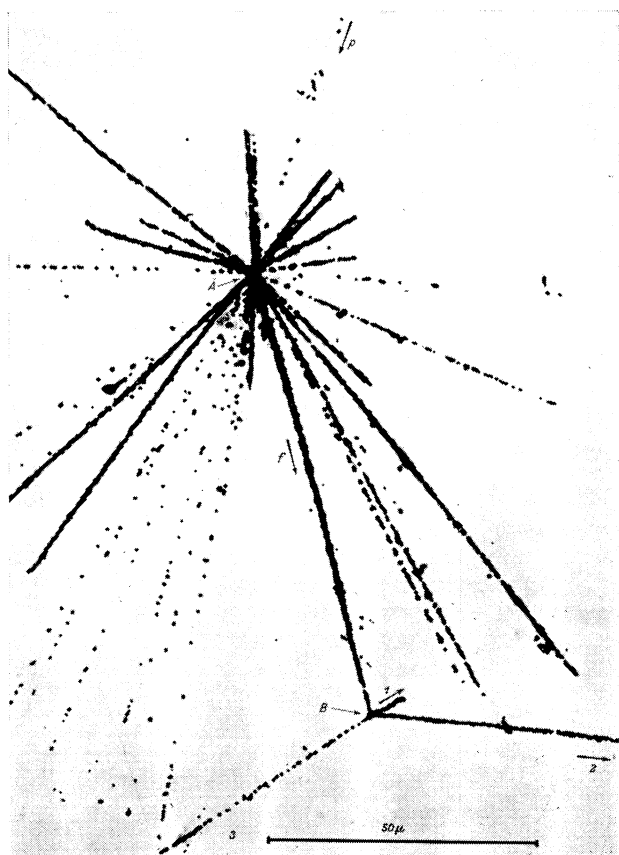
The second large collaboration is of six French Laboratories (Bordeaux, Caen, Clermont-Ferrand, Lyon, Paris and Strasbourg). They have concentrated their attention on studies of fragment and hyperfragment emission from nuclear disintegrations produced by anti-

protons of momenta up to 6 GeV/c, in addition to work on K^- meson irradiated stacks.

A large volume of emulsion irradiated by pions and protons was sent to groups outside Europe. For example, material was sent in India to the Tata Institute, Bombay, the University of Chandigarh, Cotton College, Gauhati (Assam) and Osmania University in Hyderabad; in Pakistan to the Atomic Energy Centres in Lahore (West Pakistan) and Dacca (East Pakistan); in the United States to the Universities of Arizona, Athens (Ohio), Illinois and Nebraska; and in the Soviet-Union to the Lebedev and the Atomic Energy Institutes in Moscow and Erevan, and the Institutes of Physics in Alma-Ata (Kazakstan) and Tashkent (Uzbekistan). Most of these groups are far from large accelerators, and nuclear emulsions were for them the only way (apart from cosmic-ray studies) to work in the field of high-energy nuclear physics.

Work on the construction of pulsed magnets started in the emulsion group at CERN in 1958 because it was thought then that it would be possible to obtain a significant improvement in the accuracy of determinations of momentum and charge by observing the curvatures of the tracks in very high magnetic fields. These hopes were not fulfilled, but there are other applications in which the pulsed magnets have been successfully used. They were first employed in emulsion work at the PS in a series of experiments to search for Dirac magnetic monopoles in 1961 and 1962*.

Figure 3. The first observation of a 'hyperfragment'. The nuclear fragment, f, disintegrated at B, and measurements on the tracks 1, 2 and 3 indicated that the Λ^0 hyperon was a component of the nuclear fragment. The observation, using nuclear emulsion, was made by Danysz and Pniewski of the Warsaw Group in 1953.



These were the beginnings of the type of experiment in which emulsion is used as the detector in a complex experimental arrangement.

The Λ^0 magnetic moment experiment

It is thought by many that nuclear-emulsion work is somehow different from experimental research with other techniques, that it requires the application of special skills laboriously acquired during a long period of training, and that 'emulsion workers' spend their days looking down microscopes rather like classical botanists, making up descriptions of what they see. To judge how much truth there is in this view, we will describe one of the major experiments in which the CERN Emulsion Group has participated.

The idea that it would be possible to determine the magnetic moment of the Λ^0 hyperon using nuclear emulsions and a very-high-field pulsed magnet came first to V. Z. Peterson at the California Institute of Technology (CalTec), following a theoretical paper by M. Goldhaber. In 1957, Peterson proposed such an experiment, describing many of the essential features of the project finally carried out six years later. In the background of the proposal, there was the clear need to measure the magnetic moments of the hyperons. Peterson had started to develop pulsed magnets at CalTec and nuclear emulsion was suggested as the most suitable detector because of space limitations inside the magnet, coupled with a need for very high precision in the measurements on the decay products of the Λ^0 . The idea was carried to CERN by Ph. Rosselet, then of the University of Lausanne, who worked with Peterson on the CalTec pulsed-magnet project during 1958. After his return to Lausanne in 1959, the group there (under Professor Haenny) took up the development of pulsed-magnet coils suitable for magnetic-moment experiments, and a proposal was submitted to CERN.

From 1959 to the end of 1961, a number of further proposals for the measurement of the Λ^0 magnetic moment were made by various combinations of members of the Lausanne, CERN and Bristol emulsion groups including, in one case, Peterson who visited CERN in 1960. However, progress was slow. As is often the case in experiments with nuclear emulsions, the problems were not chiefly associated with the adaptation of the emulsion technique to the requirements of the project, but were technical — engineering — difficulties which beset the development of the magnet and had to be solved by the usual methods of engineering, involving a fair proportion of progress through trial and error. Secondly, and most importantly perhaps, there was the need for the advocates of the experiment to generate enthusiasm for it, to obtain adequate support and priority and to ensure the collaboration of a sufficient number of physicists. Many other projects competed for attention and for the use of the available support facilities. Also, there was the tradition to be overcome that emulsion experiments do not require special beams, extensive facilities or large amounts of machine time.

Towards the end of 1961, it was clear that a pilot experiment — a test exposure with a π beam and a high-field pulsed magnet — would be needed to provide

* CERN COURIER, vol. 2, no. 4 (April 1962) p. 10

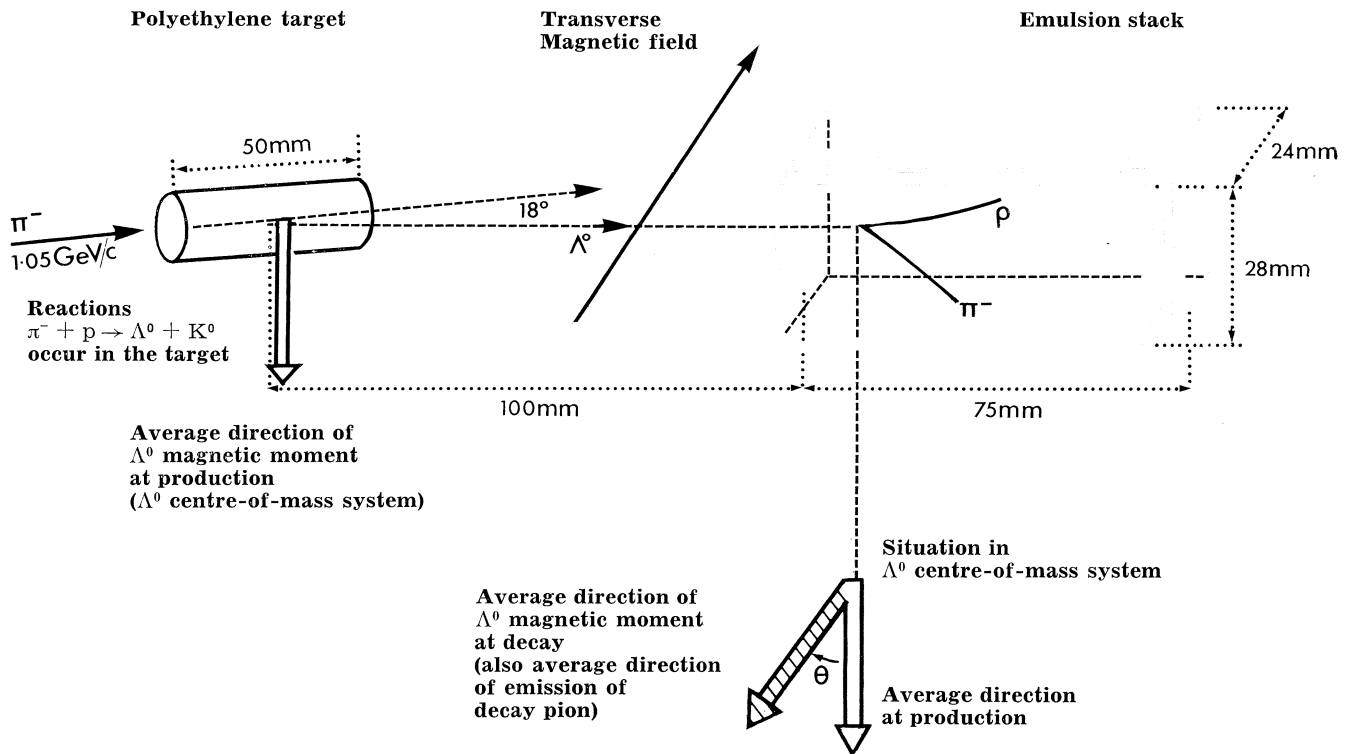


Figure 4. A schematic diagram of the Λ^0 magnetic moment experiment. The entire region shown here (target to emulsion stack) lies inside the pulsed magnetic field.

detailed data on which the design of the main experiment could be based. In particular, information was needed about the density and distribution of background tracks as a function of exposure, and about the exposure conditions (such as the intensity of the magnetic field). Also various methods of finding Λ^0 decays had to be tried to find out which was the best and what rate of detection could be expected.

It was found that an existing slow-K-meson beam could be modified to provide a flux of almost 10^5 π^- mesons per pulse, and test exposures took place in early February 1962. Most of the information needed was obtained, and it was possible to conclude that the experiment would be feasible with a magnetic field of 150 kG instead of the 75 kG used in the test runs.

At the time of the test exposures, the Lausanne/CERN collaboration also submitted a proposal for a measurement of the magnetic moment of the Σ^+ hyperon by a method similar to that for the Λ^0 . This was a very attractive proposal, for whilst it was clearly possible to measure the Λ^0 moment by counter and spark-chamber methods (and competing groups were working on this) it appeared to be very difficult to use any but the emulsion technique to find the Σ^+ magnetic moment. Accordingly, the collaboration, which had grown to include the Munich emulsion group, gave priority during the rest of 1962 to the development of the Λ^0 experiment. Approval by the Nuclear Physics Research Committee for the Λ^0 experiment was given in the Spring of 1963, and the exposures were scheduled for September.

The basic lay-out of the experiment is shown in Figure 4. Almost the whole of the region in the diagram is immersed in the magnetic field, so that the Λ^0 hyperons are in the field from production to decay.

As shown, they are 'polarized' at production such that their magnetic moments are predominantly lined up perpendicular to the plane containing the incident π^- meson and the Λ^0 itself. The interaction between the magnetic moment and the applied field results in the rotation of this direction through an angle which is proportional to the magnetic moment and other, known, quantities such as the intensity of the field. The problem is to determine this angle θ . It can be done because the most probable direction of emission of the pion in decay is the direction of the magnetic-moment vector. Thus if we measure the direction of emission of the pions from many Λ^0 decays, and transform them in each case from the laboratory system to the centre-of-mass system of the Λ^0 in question, we can find the average value of θ . The precision depends on the number of Λ^0 decays collected, on the accuracy of measurement of direction and momentum in the emulsion, and on the errors in the determination of the value of the magnetic field and of other constants associated with the apparatus.

The main run took place, without major mishaps, in October 1963. Analysis began at the four collaborating Laboratories as soon as the processed plates had been distributed, and by Spring 1964 results were beginning to emerge. The character of the work had now changed, for the many technical tasks associated with the preparation of the experiment had been replaced by scanning, measurement and data analysis. Much comparison and discussion of data took place in meetings and by correspondence, and by June 1964 it was clear that the experiment would yield an improved estimate of the Λ^0 magnetic moment. A preliminary paper was read at the International Conference on High-Energy Physics held in Dubna in September. More complete results were published in Physics Letters in March 1965.



Figure 5. The Λ^0 magnetic moment experiment. The block in the centre is the pulsed magnet containing the emulsions. The beam comes out of the quadrupole magnet seen at the top right of the photograph.

This determination of the Λ^0 magnetic moment is an example of an experiment using nuclear emulsions in a complex arrangement in which the application of many of the techniques of experimental physics, and some of engineering, was involved. The handling and processing of the emulsions, the subsequent scanning and the measurements, whilst crucial to the success of the project, did not constitute the major part of the work, nor, we might add, were they the most difficult.

We have not given an example of the other type of nuclear-emulsion experiment: the irradiation of a large stack with particles of known type and momentum, followed by analysis of the interactions with the nuclei of the emulsion. In this, the more traditional kind of emulsion work, scanning and measurement constitute the major part of the practical activities which precede analysis and interpretation.

However, the importance of the results obtained depends on the quality of the interpretation. Even the most perfect stack, irradiated to give a convenient density of events, processed to have high uniformity and low distortion, scanned and expertly measured, is only raw material for the investigation. Those who use the emulsion technique must understand and interpret their results just as any other research workers. Skill in that field is more important and much more difficult to acquire than a working knowledge of the emulsion technique.

The Present Situation

With the steady rate of development of new methods and techniques in experimental sub-nuclear physics, the range of applications in which nuclear emulsions have an advantage over other detectors has been decreasing rapidly during the last few years. As a result, most of the groups who have used emulsions

in the past have changed to other techniques, either because the change allowed them to pursue their special interests more effectively, or because in that way they hoped to have greater opportunities to take part in major developments.

Of the groups that remain active and continue to consume accelerator-produced particles, the majority are working in a clearly defined field: hyperfragment studies. A new experiment to obtain a more precise determination of the Λ^0 magnetic moment is under active preparation by a collaboration of five groups including CERN, and is scheduled at the PS for the end of 1966. Another collaboration is working on the fragmentation of nuclei of various elements by high-energy protons using a system in which energetic fragments pass through an analysing magnetic field before entering the nuclear emulsion. Both the high spatial resolving power of emulsion and the possibility of identifying nuclei coming to rest in it, are involved in this experiment.

Apart from these current applications to research, there continues to be a steady demand at CERN for beam-profile determinations and intensity surveys, where the simplicity and flexibility of the emulsion technique often makes it more convenient to use than other methods.

The future

It is always risky to predict the future in print, and especially so in the present case where there is already a long record of unfulfilled pessimistic prophecy. We do not think that the emulsion technique is dead, to be soon forgotten. It is simple, easy to adapt to new requirements, and a physicist does not need a long apprenticeship in order to use it.

As with the bubble-chamber technique, the analysis of the experimental material can be done at small university laboratories, far away from the accelerator. The investment in equipment for analysis can, moreover, be relatively modest, much less than for bubble-chamber work for which access to a large computer is always needed.

Except in special applications, such as hyperfragment studies, nuclear emulsion is basically unsuitable for the investigation of very rare events and for the detection of complex processes where neutral links travel more than a few hundred microns before giving rise to a visible secondary event. Accumulated background will swamp the rare events, unless they have very striking characteristics, whilst complex processes will usually escape detection because the background obscures the relationship between vertices connected by neutral links, and because only a very small region of the emulsion can be in view at any one time.

It is clear, therefore, that future applications will be of the kind in which one or other of the strong points of the technique is of paramount importance. Such applications have always existed since the time of Kinoshita, fifty-five years ago, and we can expect that they will continue to be found in the future. For that reason, it is important not to let the emulsion technique disappear from the arsenal available to experimental physics. It may be put into storage, perhaps, but if it remains at the disposal of those who want it, it will almost certainly continue to be used from time to time.