

THE PREPARATION OF LARGE NUCLEAR EMULSION DETECTORS AND THEIR APPLICATION TO THE STUDY OF K-MESONS AND HYPERONS

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ABSTRACT

A method is described for constructing out of individual sheets of nuclear emulsion a detector of large volume and stopping power which can be used for observing entire chains of successive nuclear interaction and decay processes initiated by high energy particles.

Such a detector which had been exposed for several hours in the stratosphere has proved particularly valuable for detecting K-mesons and Hyperons* and for studying their modes of production and decay.

I. INTRODUCTION

NUCLEAR emulsions have, during the past six years, become one of the most useful and accurate tools for studying the properties of subatomic particles and their interaction with matter. They have been especially useful in investigating the long chain of nuclear and electromagnetic interactions and successive decay processes by which the incident cosmic ray energy is first distributed among stable and unstable particles and then dissipated in the traversal of the atmosphere or other materials.

One of the main limitations of the usefulness of the nuclear emulsion technique arises from the requirement that the emulsion must be sufficiently thin to permit microscopic examination with high resolution. In practice this limits a nuclear emulsion detector to a thickness of the order of one millimeter and it is therefore rare that more than a small fraction of the chain of interaction and decay processes is observable in any particular case.

Large detectors consisting of a carefully aligned assembly of glass plates coated with nuclear emulsions have been employed since 1948.¹ In such

* The term "K-meson" designates an unstable particle whose mass is intermediate between that of the π -meson and the proton.

The term "Hyperon" designates a particle whose mass is intermediate between that of the neutron and the deuteron. This designation was suggested at the Cosmic Ray Congress held at Bagnères-de-Bigorre in July 1953.

detectors, tracks of particles which traverse the plate assembly can be traced from emulsion to emulsion through the intervening glass plates and therefore the behaviour of the particles can be observed intermittently over distances of the order of several centimeters. From the spacing of successive emulsions, and the position and orientation of a track segment in one emulsion one can predict in the succeeding emulsion an area where the continuation of the track ought to appear if the particle was not absorbed or appreciably scattered in the intervening glass plate. The correct identification of the continuation of a track or group of tracks requires, therefore, that they are clearly distinct from other tracks which traverse the predicted area.

This type of detector has proved very useful for tracing heavy primary nuclei of the cosmic radiation or groups of parallel tracks representing the core of high energy showers,^{2, 3} because such tracks or configuration of tracks are clearly distinguishable from the general background; it is not however suitable for tracing fast singly charged particles or slow particles which suffer considerable scattering in the material between emulsions. It is of course also a disadvantage of such a detector that a large fraction of the particle trajectories lies in the glass backing of the emulsions and is not available for observation.

In order to overcome these limitations we have constructed a large detector consisting of emulsion only. This block of emulsion was composed of individual unbacked emulsion sheets and it was our objective to subsequently align the processed emulsions with sufficient accuracy to permit tracing the entire chains of interaction and decay processes which are initiated in the block by high energy cosmic ray particles.

The same problem has recently also been considered by Powell⁴ and by Stiller *et al.*⁵ and apart from minor differences in development procedure the method which we finally adopted differs mainly in the higher accuracy aimed at and achieved in the alignment of emulsion sheets after development; this we believe to be of great value in heavily exposed plates and in general in such cases where (as in the tracing of fast singly charged particles) the general background of similar tracks is fairly high.

The ideal solid emulsion detector is obviously one in which emulsion sheets exposed in a tightly packed block are subsequently, for the purpose of microscopic examination, mounted on slides in such a manner that if put on the microscope stage, the exit point of a given track in the upper emulsion coincides with the entrance point in the next. This ideal superposition over an entire slide has not been achieved for two reasons:—

(a) The emulsions even when tightly packed for exposure are not flat and gaps between adjoining surfaces vary from zero to about 0.15 mm. Thus the exit and entrance points do not coincide but rather are separated by an unknown distance along the direction of the track (this distance is smaller the steeper the track).

(b) Since in the method which we finally adopted the emulsion is mounted on glass *before development*, distortion moves the exit point on the air surface from its proper position such that exit and entrance points cannot simultaneously be aligned for all tracks.

An emulsion block satisfactory for all purposes would be one in which the two points lie along the line of the track with an error of not more than 10-15 μ . If such alignment can be achieved, even minimum tracks in a heavily exposed plate can be traced through many emulsions, high magnification can be used for observation and no acceptable alternatives for the true continuation will present themselves. It must be remembered that if in a track passing ~ 20 emulsion sheets, possible alternatives present themselves only once or twice the work of following becomes very laborious indeed.

In our stack we have achieved a line up with an error of $\sim 50 \mu$. This error is mainly due to distortion. It makes it possible to trace any particle whose track is heavier than minimum without any uncertainty or delay. The tracing of minimum particles however is still difficult. If the track is too steep the background in a circle of 50μ radius is often too high to make a definite assignment. If the track is very flat the entrance and exit points are far separated along the track by an unknown amount (due to the gap between emulsion sheets) and again a number of possible alternatives present themselves. In our case a thin layer on the air surface of the emulsion is less sensitive than the remaining volume which makes the assignment of the exit point of flat minimum tracks still more difficult.

In spite of these inaccuracies which could certainly be reduced when techniques of packing and processing are improved, the block detector which we have constructed has proved very useful in locating heavy unstable particles, determining their origin, their mass and the nature of their decay products. Examples of problems for which the detector has proved superior to ordinary nuclear emulsion detectors are given in Section III.

II. CONSTRUCTION OF AN EMULSION BLOCK DETECTOR

Twenty-four sheets of Ilford G-5 emulsion 4" \times 6" and 600 μ thick, separated by thin paper sheets, were used to construct the emulsion block. Even before exposure in the stratosphere the emulsions had been subjected to an

appreciable exposure during the air transport from England to India. We have been able to distinguish events which were recorded at airplane altitude from those which occurred in the stratosphere, because the plates were repacked just before the balloon flight. Thus when the processed plates were later lined up, only tracks which occurred during the balloon exposure could be traced from plate to plate, while pre-exposure tracks had in general no continuation in the adjacent emulsion. The assembly of emulsion sheets was placed between two bakelite plates and the resulting block was tightly wrapped with adhesive tape. The block which was finally used in our experiments was exposed in a balloon flight in September 1952 at geomagnetic latitude 19° (Delhi). The balloons reached an altitude of 90,000 feet and remained above 70,000 feet for $4\frac{3}{4}$ hours.

The requirement that the emulsions after development can be brought back accurately into the relative position which they occupied during exposure implies:—

(a) that two emulsion sheets which had equal overall dimensions before exposure still have equal though not necessarily the same dimensions after processing, and

(b) that development introduces no appreciable local distortions in the emulsions.

We have tried two different methods for obtaining a set of plates satisfying these conditions. In the first method we developed and dried the emulsion sheets before mounting them on glass plates. Here the local distortions could be kept extremely low, but the overall dimensions of the processed sheets could not be controlled with sufficient accuracy to satisfy condition (a).

In the second method the emulsion sheets were mounted on glass plates before processing. With this procedure we could satisfy both conditions well enough to enable us to construct a detector which is satisfactory for tracing all particle tracks whose grain density is clearly greater than minimum grain density. However, local distortions introduced during processing proved to be the limiting factor in obtaining an accuracy sufficiently high to permit the unambiguous tracing of minimum ionization tracks.

The temperature method of Dilworth *et al.*⁶ was used for all developments. Processing solutions used were essentially the same as recommended by Dainton *et al.*⁹

A. *The First Method (The emulsions are developed and dried before being mounted on glass plates)*

Throughout the processing except during the "hot" stage, each emulsion sheet was kept floating in a separate glass dish whose bottom was covered

with a sheet of paper. After the washing stage the emulsions were dried by replacing the water in the dish slowly with an alcohol-water mixture, the alcohol concentration being increased by 10% every four hours until the bath consisted of concentrated alcohol. 5% glycerine was added to the bath at the beginning of the drying process and the glycerine content was kept constant throughout.

After drying the sheets were mounted on glass plates. The detailed procedure adopted for processing, drying and mounting is discussed in Appendix I.

When treated in this manner the emulsions showed no measurable distortion. Displacements between the air and glass surfaces were less than 3μ which for plates of 600μ thickness corresponds to a distortion of less than 10 covans. Nevertheless these plates were not suitable for constructing an emulsion block detector because the emulsions which were all equal in size ($4'' \times 6''$) before processing differed by as much as 2 mm. from each other after drying. Thus the entrance and exit points of tracks in adjacent emulsions could not be brought into coincidence simultaneously in all regions of the plate.

B. Second Method (The emulsions are mounted on glass plates before development)

The procedure for mounting the undeveloped emulsions was as follows: A few drops of a solution consisting of 50% distilled water and 50% alcohol are applied to the surface of treated glass plates supplied by Ilford. These drops spread rapidly over the entire surface and swell the thin gelatine layer. The dry emulsion sheet is then placed on the glass and pressed down firmly with a hand roller. When this procedure was followed carefully, no bubbles developed in the emulsion during processing. In a later experiment with a different batch of emulsion however, we found that often bubbles formed during the late fixing stage and that application of the alcohol-water mixture with a cotton swab to the emulsion surface in addition to its application to the glass surface was a more satisfactory procedure.

Method of processing was similar to that employed by Dainton *et al.*⁹ while the drying procedure was identical with that used in the first method.

In these plates local distortions were moderately large; displacement vectors of length up to 40μ were measured in various regions of the plates corresponding to distortion values up to 110 covans. Another unsatisfactory feature of this particular set of plates was a sharp drop in sensitivity towards the air surface. This effect which we encountered here for the first time has

recently been attributed by Occhialini⁷ to corrosive action of fresh hypo during the late fixing stage.

C. *The Lining up of the Microscope Slides*

The plates after drying were cut into four parts yielding 2" × 3" slides, a size which is suitable for the microscope stages used in this laboratory. Next, three or four tracks of very heavy primary particles of different orientation were selected in various parts of the plate, tracks which were sufficiently prominent such that they could easily be traced from plate to plate even with the imperfect alignment which the slides presented at this state.

Then we prepared a carefully machined set of rectangular frames made of transparent plastic of $\frac{1}{8}$ " thickness; the outside dimensions of these frames were slightly larger, their inside dimensions slightly smaller than the 2" × 3" slides on which the emulsions were mounted. The first slide carrying the emulsion which formed the outside face of the block was firmly glued on to one of these frames. The next slide carrying the adjacent emulsion was glued to another frame with a slowly drying cement; its position could, therefore, be adjusted slightly for about 30 minutes. These 30 minutes were used to put the slide on the microscope stage and shift it in such a manner that if the first and second slide were alternately put into the slide holder, each of the previously selected track segments in one plate represented an exact continuation of the corresponding track segments in previous plate. After the second slide was correctly placed the same procedure was used for gluing the third slide to its frame. In this manner all slides were mounted on frames. With some practice it is then possible to mount the slides such that their relative position in the slide holder is within 10 μ the same as the relative position they occupied during exposure. This error is, therefore, small compared to the about four times larger misalignment of track segments arising from distortions in the emulsion.

Although our procedure for lining up the plates was somewhat laborious, and required practice we feel that the effort spent on obtaining this relatively high accuracy was amply justified by the rapidity and confidence with which tracks could later be traced through the block. The complete assembly of emulsions lined up to reproduce the relative position they occupied during exposure we shall call an *Emulsion Block Detector*.

III. ON THE APPLICATION OF EMULSION BLOCK DETECTORS TO THE STUDY OF UNSTABLE PARTICLES

Once such a detector has been constructed it offers many advantages over the conventional detectors consisting of single nuclear plates or of an

assembly of nuclear plates. Details of the experimental results which have been obtained so far are given in the separate papers listed in the footnote.† Here we confine ourselves to mentioning some of the investigations for which such a detector is particularly well suited.

(a) *Investigations of the origin and the properties of slow K-mesons and Hyperons*

It is well known that charged and neutral K-mesons exist which decay in such a way that at least one of the decay products is a charged π -meson. Well established among these are the τ -mesons ($\tau \rightarrow 3\pi$) and a neutral particle which has been variously designated by the symbols ν^0 , V_2^0 and V_4^0 and for which the symbol θ^0 has recently been suggested ($\theta^0 \rightarrow \pi^+ + \pi^-$). There is also at least one Hyperon (usually designated by V_1^0 but for which we now shall use the recently suggested symbol Λ^0) which gives rise to a charged π -meson upon decay ($\Lambda^0 \rightarrow \pi^- + p$). Only a very small number of such particles have so far been found by scanning nuclear emulsions and often the conditions of observation did not permit accurate measurements. The emulsion block detector permits a systematic search for such particles by tracing π -mesons which come to rest in the block backwards towards their origin. Uptil now we have traced about 600 slow π -mesons. This work did not only yield information on the creation and the energy spectrum of π -mesons produced in nuclear interactions but also led to examples of the decay of τ -mesons and other unstable heavy particles.

A similar search is now in progress for rare unstable particles among whose decay products are charged slow μ -mesons, the existence of such particles being indicated by the observation of O'Callaigh.⁸

Once such rare particles are located either by the tracing of their decay products or by other means, the conditions of observation in an emulsion block are usually favourable for obtaining accurate measurements. Appreciable track length is usually available permitting good determination of the particle mass; furthermore, in many cases the particles themselves can be traced back to their origin in some nuclear event and therefore information is obtained on the mode of production and on the lifetime. Thus out of 14 K-mesons and charged Hyperons observed and traced by us, 11 were found to originate in some nuclear event in the emulsion block. Similarly

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- † (i) "Properties of Heavy Unstable Particles," D. Lal, Yash Pal & B. Peters, *Phys. Rev.* (In press).
(ii) "Observations on τ -mesons and on K-mesons giving rise to Capture Stars," D. Lal, Yash Pal & B. Peters, *Proc. Ind. Acad. Sci.* (In press).
(iii) "An Improved Method of Determining the Mass of Particles from Multiple Scattering Versus Range and its Application to the Mass of K-mesons," S. Biswas, E. C. George & B. Peters, *Proc. Ind. Acad. Sci.* (In press).

by tracing the charged decay products from the decay point on through the detector, information is frequently obtained on their mass, energy and interaction properties. Because of these favourable observational conditions it was possible to obtain improved mass values for the τ -meson, to establish definitely the existence of K-mesons which when at rest are captured by nuclei and give rise to capture stars, and to obtain an accurate Q-value for the decay of the Λ^0 Hyperon.

(b) *Study of high energy nuclear interactions*

Very large showers are easily located in an emulsion block detector. One may either trace any accidentally observed group of parallel minimum ionization tracks back to their origin or one may trace energetic heavy primary nuclei through the block. Both methods frequently lead to the location of large showers and about 8 showers with shower particle multiplicities between 40 and 150 have been located in our detector with comparatively little scanning effort. Such events are well suited for studying the interactions of fast shower particles, since many meters of integrated track length can easily be accumulated. Conditions are also favourable for determining the relative number of π^0 -mesons and of other interacting neutral shower particles produced in such high energy nuclear interactions.

These examples illustrate that the emulsion block detector is well suited for many investigations which cannot be undertaken or are extremely laborious with the more conventional nuclear plate arrangements.

During the exposure in the stratosphere, as well as during recovery, processing and other steps which led to the construction of our emulsion block detector, we had assistance from many sources which we gratefully acknowledge. Our special thanks are due to Mr. C. Waller of Ilford Limited, to the Department of Physics at the University of Delhi, in particular to Professor D. S. Kothari as well as to our colleagues, Mrs. S. Mitra, and Messrs. G. Friedmann, P. N. Krishnamurthy and M. S. Swami.

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APPENDIX I

PROCESSING OF STRIPPED EMULSIONS BEFORE MOUNTING THEM ON GLASS PLATES

Distortion of emulsion during processing is due to the relative shift of the different layers. In the case of an emulsion which is processed after being mounted on a glass plate the lower surface of the emulsion is constrained to keep its size during all the operations of processing, while the other layers are shifted due to expansion and contraction of the emulsion in different stages. If these layers do not come back to their original position after the processing, the emulsion is said to be distorted, because the tracks traversing different layers will have changed their shape. It would seem that if one could process a stripped emulsion without pasting it on glass surface, the emulsion would move as a whole during the expansion and contraction processes and relative shifts of the layers could be avoided. In order to investigate the possibility of obtaining *distortion free* emulsions experiments were initiated to process emulsions without glass backing.

Processing

The strips were processed in small dishes, one in each dish. The dishes were sufficiently larger than the emulsion strips to allow for the expansion of the emulsion in the fixing and washing stages. Between the glass dish and emulsion surface a smooth stiff paper was placed during all stages of processing in order to avoid the danger of the emulsion sticking to the glass and getting distorted. The sheets must not be handled during processing.

Problem of sticking during hot stage

A glass plate was inserted below the paper sheet and the emulsion was then lifted from the dish and placed on a warm metal base. As the hot stage proceeds the emulsion becomes soft and has a tendency to stick to the paper on which it is lying. This introduces serious distortions because the places where the paper sticks are constrained to keep their position while the rest of the emulsion is changing in size. Several types of paper were tried to avoid the sticking trouble. Ultimately it was discovered that the nature of paper surface is not so important. Any paper of good strong texture is satisfactory. The important thing is to keep the temperature in the hot stage below 28°C . It was found that a temperature of $28^{\circ}\cdot 5$ is rather critical; the emulsion loses its jelly like structure and becomes soft. If the hot stage temperature is kept low and emulsion is not allowed to become soft, sticking does not occur.

After the hot stage the strips were directly introduced into the cold fixing bath. Change of fixing solutions was very frequent in the beginning and less so in the later stages. As the fixing takes place from both sides,

the fixing process is much faster than for mounted plates. The strips (600 μ) cleared in less than 24 hours.

Washing

Strips were washed in running water. Washing time was much shorter than needed for mounted emulsions. In washing, the strips increase by nearly 50% in their linear dimensions.

Drying

Most of the distortion in the processing of mounted emulsions is introduced in the process of drying. Drying of unbacked emulsions presents a special problem. It would be very difficult to dry such sheets in air without introducing serious distortion. We therefore dried the plates by extracting the water with alcohol. The strips were immersed in an alcohol-water mixture whose alcohol concentration was increased by 10% every 4 hours until all water had been removed. Each alcohol bath contained from 3% to 5% glycerine, which keeps the emulsion soft. The temperature of the alcohol-water mixture was kept below 10° C.

Mounting

After the strip is removed from the alcohol it is placed under slight pressure between two glossy cardboard surfaces until the alcohol is completely evaporated. Next the underside of the emulsion is coated with a thin plastic layer by painting it with a solution of Durofix† cement in acetone. After this layer is dry the emulsion is pasted with a commercial glue‡ onto a glass plate heavily coated with gelatine.

The plastic coating was found to be necessary in order to avoid a softening of the emulsion surface by the glue which will lead to distortion. The gelatine coating on the glass plate must be heavy in order to take up the moisture contained in the glue; otherwise the evaporation of the water in the glue will raise bubbles and lift the emulsion off the glass surface.

Controlling the size of the strips

Unbacked emulsions will during different stages of processing not only alter their thickness but also change their linear dimensions. The biggest dimensions which the emulsion attains occurs during the washing stage (1½ times original). It was found that the maximum size attained depended on the hypo which was used. Two types of hypo were tried.

(i) Pure 40% sodium thiosulphate solution in initial stages and 40% sodium Thiosulphate solution plus 5% sodium sulphate after clearing.

† Product of The Rawplug Company Limited, Cromwell Road, London, S. W. 7.

‡ Product of Camlin Limited, Bombay 28.

(ii) 40% sodium thiosulphate plus 3% sodium metabisulphite.

The expansion of the emulsion was smaller when the second type of fixing bath was used.

When the alcohol drying process starts, the emulsion strips become smaller till in about 70% alcohol water solution the size is almost equal to that of the strips before processing. However, the size continues to decrease as the drying proceeds. It is expected that if all the emulsions were treated exactly in the same way during processing, and treated in the same alcohol baths for drying, their final size should be exactly equal though smaller than their original size. However, it is sometimes found that two strips which have been processed together have slightly different sizes as they progress through different drying baths. It seems that their sizes can be manipulated to some extent by altering the concentration of glycerine in the drying baths. The higher the concentration of glycerine, the less will be contraction of the emulsion in the drying stage. It was also found that the contraction a strip will undergo in a bath depends on the temperature of the bath. The higher the temperature the greater the contraction. These findings coupled with the knowledge that the only way of increasing the size of a strip which has contracted too much is to put it back in a bath of greater water content, could be used to control the final size of the strips to a large extent. Nevertheless it seemed unlikely that the final dimensions could be controlled with sufficient accuracy (≤ 0.1 mm.) to make such emulsion sheets useful for the construction of an emulsion block detector.

Stress release during hot stage

A series of emulsions were under observation during hot stage. Temperature of the hot stage was $\sim 28^\circ$ C. Even though the emulsions did not stick to their base paper, some of them were seen to warp. This is believed to be due to release of stresses in the emulsion, which, being free to move on its base loses its rectangular shape. There seem to be two methods for avoiding this distortion. One of them is to work at a sufficiently low temperature [$< 20^\circ$ C.] so that the emulsion does not become soft and the stresses remain frozen in it. The second is the method of releasing the stress of the emulsion prior to exposure, as suggested by Stiller *et al.*⁵

Some of the emulsions however, did not show any signs of warping during the hot stage. These emulsions when mounted showed very little distortion. Displacements between the air and glass surfaces were less than $3\ \mu$, which for plates of $600\ \mu$ thickness corresponds to a distortion of less than 10 covans. Emulsions treated in the manner described here could be very useful for scattering measurements on high energy particles.