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Publication Date

1959-04-01

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UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California
Contract No. W-7405-eng-48

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Edward C. Calhoon and Glen W. Watson

April 1959

Printed for the U. S. Atomic Energy Commission

PARTICLE DETECTORS USED IN HIGH-ENERGY PHYSICS*

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**Lawrence Radiation Laboratory
University of California
Berkeley, California**

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Experiments in high-energy physics are directed toward discovering the origin of the intense but short-range force that binds the nucleus together. The method most widely used in this study is to bombard the nucleus with particles having sufficient energy to split it into its elementary parts. Many of the new particles created in these collisions are unstable and decay into other types of particles within a billionth of a second or less. For an experiment to be meaningful, the physicist must be able to measure such things as the energy, electric charge, and mass of the particles involved, as well as the forces existing between the particles. To do these things requires highly specialized detecting equipment.

We may speak of particle detectors as belonging to two classes -- the counters and the visual detectors. The counters count the number of charged particles passing through their sensitive element, whereas the visual detectors give a picture of the tracks formed by the particles. The two types of counters which are employed in high-energy physics are the scintillation counter and the Cherenkov counter. Because the scintillation counter is the most widely used of the two, we will describe it in some detail.

A scintillation counter consists of two basic parts: a material which emits a flash of light (scintillation) when a charged particle passes through it, and a device for observing this scintillation (Fig. 1). Some of the more common scintillators (phosphors) are anthracene, an organic

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* Work done under the auspices of the U. S. Atomic Energy Commission.

solid; argon, an inert gas; sodium iodide, in its crystalline form; and vinyltoluene, a plastic. Plastic scintillators are becoming more popular, since they can be easily formed into rings or other complex shapes.

Prior to the development of vacuum-tube circuits, the scintillations were observed visually. Unfortunately, the human eye is not sensitive enough nor the brain quick enough to catch all the faint flashes of light and to record the precise time at which each occurred. Imagine trying to count the number of sparks that fly off a grindstone and attempting to clock each one with a stopwatch. Yet nuclear particles are infinitely more elusive than sparks. Therefore, to observe the scintillations, we use a photomultiplier tube. When it sees a flash it sends an electric signal to an electronic device which counts the event. Perhaps an illustration will make this clearer.

A simple experiment using scintillation counters is shown in Fig. 2, where it is desired to count the number of particles of a given velocity v traversing the two counters. If we know the distance d separating the counters, the time of flight t of the particle is simply $t = d/v$. For instance, if the counters are placed 10 meters apart, and if we want to count the number of particles having a velocity equal to one-tenth the speed of light (3×10^7 meters/sec), the time of flight is

$$t = \frac{10}{3 \times 10^7}$$

$$t = 0.33 \times 10^{-6} \text{ second.}$$

What we must do then is set up the electronic apparatus so that it will record only those particles traversing the distance in this precise time. To do this we insert a time delay of 0.33×10^{-6} second in the electric line leading from counter S-1 to the coincidence circuit. The signals reaching the coincidence circuit will be in exact time coincidence for only those particles having the desired velocity. Whenever the coincidence circuit receives two simultaneous input signals it gives an output signal to the scaler, which counts the event. Usually, the scaler is set to count only a given percentage of the input pulses, say 10%.

A counting experiment utilizing the principle illustrated above was used in 1955 by Drs. Chamberlain, Segré, Wiegand, and Ypsilantis, of

the Lawrence Radiation Laboratory, to discover the antiproton. In their experiment they set the time delay so that only those particles traveling a distance of 40 feet in the exact time of 51 billionths of a second would be recorded. Since none of the other negatively charged particles present could have that exact velocity, these signals could be caused only by antiprotons.

The scintillation counter is very useful because of its sensitivity, its extremely short time resolution (10^{-9} sec), and its simplicity. But its spatial resolution of about 1 millimeter is so poor that it is worthless for measuring such thing as the angle between the tracks of two particles produced in a collision or decay. To do this, we must use one of the visual detectors. This class of detectors includes the nuclear emulsion, the Wilson cloud chamber, the diffusion cloud chamber, and the bubble chamber.

The simplest of visual detectors is the nuclear emulsion. An emulsion stack consists of a number of layers of special photographic film called "pellicles." Charged particles passing through the stack expose the film so that when it is developed we see black tracks on a light background.

The nuclear emulsion has the best spatial resolution of any particle detector -- about 0.1 micron.* This makes it invaluable for studying particles having very short half-lives, since they leave short tracks. Also the nuclear emulsion has the highest "stopping power" of the visual detectors, but this is a mixed blessing. The events are so numerous and the tracks so crooked that the effect of a magnetic field on particle curvature cannot be measured.

A major drawback to the emulsion technique is that each pellicle has to be painstakingly examined by a highly trained microscopist, who carefully measures coordinates points and grain density along the particle tracks. Until recently, these data had to be manually entered into a log. Later a physicist would use this information to perform tedious and complex calculations. The schedule of a ten-man research team might have read something like this: one day to expose the emulsion stack; one year to measure

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* A micron is a millionth of a meter.

the tracks and record the data; another year to perform the calculations and analyze the results. In the enormity of their task they might have been likened to the Norse god Thor, who was challenged by Utgard-loki to drain a hunting horn with three drafts. Unknown to Thor, the horn was connected to the sea, so that no matter how long or how hard he tried he was unable to empty it, though each time he drank the oceans ebbed.

A recent invention by a group of scientists and engineers under the leadership of Dr. Walter Barkas of the Lawrence Laboratory has improved this situation remarkably. With the digitized microscope which they developed, an operator needs only align the cross hairs of the microscope on the particle track and then push a button (see Fig. 3). The three coordinates of the point under the crosshairs are automatically recorded on an IBM card. This process must be repeated for each coordinate point taken, so it is still a time consuming task. Even so, the taking of data has been speeded up by a factor of about eight over the earlier manual methods. The great advantage of this system is that once the data are on IBM cards, a digital computer can quickly and reliably perform the involved calculations.

The Wilson cloud chamber does not possess the limitations of the nuclear emulsion, but it has others of its own. A cloud chamber consists of a vessel containing moist air or gas in a supersaturated condition. A charged particle passing through the chamber leaves a visible trail of liquid droplets which can be readily photographed. Placing the chamber in a magnetic field causes the charged particles to curve in flight. The direction of curvature tells us whether the particle carries a positive or negative charge; the amount of curvature depends on the magnitude of the charge and on the momentum of the particle. Accurate calculations of the energy absorbed or released in a reaction can be made based on the momentum measurements.

Unfortunately, the cloud chamber has several inherent disadvantages. A beam pulse is available from a particle accelerator like the Bevatron every 6 seconds, but a cloud chamber has a dead time of a minute or two. Also, only a small percentage of the photographs contain interesting events. This is because the gas in a cloud chamber is not very dense, and relatively few bombarding particles strike a target nucleus. For these

reasons, a cloud chamber is inefficient in utilizing the available beam, which is produced at considerable expense.

In an attempt to overcome these difficulties, the diffusion cloud chamber was developed, in which the gas is put under a pressure of 30 to 40 atmospheres to increase its density. This device is continuously sensitive but only in a very shallow area. The many reactions that occur either above or below this region are invisible.

A device embodying most of the merits of the visual detectors mentioned so far without retaining their principal disadvantages is the bubble chamber, invented in 1952 by Dr. Donald Glaser of the University of Michigan. Instead of a gas, a bubble chamber uses a liquid as its sensitive medium. Because of its much greater density, a liquid can be operated at relatively low pressures and still have very good stopping power for the incoming particles. Yet the stopping power is not so great that confusing tracks are produced, as is sometimes the case with the nuclear emulsion.

Another advantage of the bubble chamber is that it is sensitive throughout its entire volume, which may be quite large.* Moreover, its dead time is very brief -- a photograph can be taken every few seconds. It has a time resolution of several microseconds, not quick enough for determining particle velocity, but adequate for distinguishing separate events. And finally, if liquid hydrogen is used then we have an ideal target, since there is no ambiguity as to what the struck nucleus is.

It was with a liquid hydrogen bubble chamber that a group of physicists, headed by Dr. Luis Alvarez of the Lawrence Laboratory, recently discovered the last of the elementary particles of ordinary matter which have been predicted to date. This is the xi zero, or neutral cascade hyperon -- a particle about 25% heavier than a proton. Because the xi zero carries no electric charge, it leaves no track in a bubble chamber. Its existence must be inferred from the tracks leading up to the point where it was created and those following its decay.

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* A bubble chamber containing 520 liters of liquid hydrogen was successfully operated in March at the Lawrence Radiation Laboratory (see Fig. 4). Several other large bubble chambers are now under construction at other research centers throughout the world.

A stereoscopic camera is used when taking bubble chamber photographs, in order to obtain a three-dimensional effect (see Fig. 5). If this were not done, the path of the particle in real space could not be reconstructed mathematically and no usable information would be obtained. Therefore, it is necessary to measure the two-dimensional coordinates of points along the tracks in each stereo view. This is a very tedious job when done with a conventional measuring microscope.

To facilitate the taking of data, a device called "Franckenstein" has been developed (Fig. 6). Franckenstein was designed and built at Lawrence Laboratory by a group headed by Jack V. Franck. This machine projects the film onto a screen, where, with a minimum of manual control, the coordinates of tracks in each stereo view are automatically measured and punched into IBM cards for later analysis with a digital computer. The fascinating feature of Franckenstein is that the operator need only align the optical index with the track in an approximate fashion, and the machine will lock on the track. The operator then uses a "foot pedal" to drive along the track, periodically pushing a button to record coordinate information.

This seemingly impossible feat is made possible by a scanning unit consisting of a photomultiplier tube and electronic time discriminator, which feed correction information back to the servomotors that drive the film carriage. This process is analogous to the operation of an automatic pilot which keeps an airliner flying on the beam.

With Franckenstein, all the necessary data from a pair of stereophotographs can be measured and recorded on IBM cards in from 5 to 10 minutes, on the average. With the earlier methods more than an hour was required for these steps, and then the information was often inaccurate owing to human errors. Franckenstein can measure a coordinate point of a particle track to an accuracy of 1 ten-thousandth of an inch (on the film), and it makes no mistake.

Equipped with a "drinking device" as marvelous as this, the god Thor might even have succeeded in draining the oceans, and thus have won his wager with the capricious giant, Utgard-loki.

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LEGENDS

- Fig. 1 One type of scintillation counter. A particle passing through the phosphor causes a flash, which is reflected by the foil onto the photocathode. Electrons are emitted which in turn strike successive stages of photocathodes, so that an amplified electrical signal is produced at the output.
- Fig. 2 A simple experiment with scintillation counters (S-1 and S-2).
- Fig. 3 Semi-automatic microscope used in scanning nuclear emulsions. Its inventors are Conrad Mason (left), Dr. Walter Barkas (center), Thomas Taussig (right), and James Hodges (not shown).
- Fig. 4 Model of the 72-inch liquid hydrogen bubble chamber recently completed at the Lawrence Radiation Laboratory.
- Fig. 5 Stereophotographs taken with a liquid hydrogen bubble chamber, showing an interaction between a K^- meson and a proton. The collision results in a lambda hyperon (Λ), which decays into a π^- meson and a proton. Since the lambda hyperon carries no charge, it leaves no track. The spiral tracks to the right and left are those of electrons.
- Fig. 6 The Franckenstein film-measuring projector. Its inventors are Jack V. Franck, Jerome Russell, Edson Skiff, and Dr. Hugh Bradner.

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Fig. 3

Fig. 4

Fig. 5a - Left

Fig. 5b - Right

Fig. 5c

Fig. 6