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High Energy Physics

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Without a little further explanation the title of this article may not convey a definite meaning to all readers, so I would like to start by pointing out that "high energy" refers to the energy of individual bombarding particles used to produce nuclear disintegrations, and not to situations where a large aggregate amount of energy is involved, as in an atomic power plant. The next question might be, when is energy considered "high"? To discuss this, we need a scale for measuring particle energies, and some feeling for the meaning of magnitudes on this scale. The basic scale unit is the "electron volt", which is the amount of energy acquired by a particle bearing an electric charge equal to that of an electron, when it falls through an electrical potential difference of one volt. This unit is rather small for use in nuclear physics, so a million electron volts, abbreviated "Mev", is the commonly used unit.

Now we can establish a feeling for magnitudes. Atomic nuclei are made of protons and neutrons (collectively called "nucleons"), and are held together by strongly attractive forces. The amount of energy required to

extract a nucleon from a nucleus is called the "binding energy" of that nucleon; such binding energies are of the order of magnitude of a few Mev. (Contrast this with the chemical binding energies of atoms in molecules, which have magnitudes of a few electron volts.)

Another sort of meaning can be attached to energy, in terms of the mass to which it is equivalent according to the much-discussed relativistic relation between mass and energy. On this scale, the mass of a nucleon corresponds to nearly a thousand Mev of an electron to 1/2 Mev, and of the most easily made mesons (see later sections for further discussion) to 135 Mev. Now, if we rather arbitrarily define a "high energy process" as one in which the energy of the incident particle is ^{many times as} large as _^ the binding energy of a nucleon in the bombarded nucleus, we arrive at a lower limit (not sharply defined) of around 100 Mev for high energy processes. By an interesting coincidence, this is not too far from the energy at which meson production starts.

Thus the experimenter in this field has two kinds of things to investigate. First, there are the "ordinary" kinds of nuclear reactions, in which aggregates of nucleons are simply broken up or rearranged. The fact that the bombarding energy is large compared to the binding energy can in some

cases (but not all) simplify the theoretical interpretation of such reactions. Second, there are the more recondite processes in which new particles are created. High energy particles suitable for performing such experiments can be found in the naturally occurring cosmic rays, but more intense and controllable sources are provided by particle accelerators. Therefore let us start by taking a short look at some of these machines. I shall use as illustrations those at the University of California at Berkeley, since I am more familiar with them than with similar accelerators located elsewhere.

Particle Accelerators

The best known machine is the great synchro-cyclotron (Fig. 1), which can accelerate protons to an energy of 350 Mev. Just behind the two men is one corner of the ~~xxxx~~ square vacuum chamber inside which the protons move, in circular orbits which start at the center and expand outwards to a diameter of 14 feet. The large overhead beam and the white circular tank *beton* are parts of the magnet which holds the protons in their orbits; the complicated-looking equipment in front of the men delivers the electrical impulses which ~~xxx~~ speed up the protons to high energy. This is an early picture; one taken now from the same spot would show nothing but a massive concrete wall, the

shield which stops penetrating radiations produced by the cyclotron when operating.

Next there is the synchrotron (Fig. 2), which accelerates electrons to 330 Mev. Note that the machine is much smaller than the cyclotron, although the particle energy is about the same while the general structural outline and the basic principle of operation are closely related. The relatively small size is accounted for by the fact that an electron is much lighter than a proton; for a given energy and magnetic field strength, the lighter particle travels in a circular orbit of smaller diameter than the heavier one. You might inquire, why have both protons and electrons at high energy? The fact that different particles produce different effects is a sufficient answer to the physicist.

Finally, there is the Bevatron (Fig. 3). (This name, unlike the others, belongs to the individual machine, and is derived from the initials for "billion electron volts". In principle of operation, the bevatron is closely related to the cyclotron and synchrotron, and a generic or descriptive name could be "proton synchrotron".) The machine is too large to get completely into the picture; the magnet has degenerated into a shell which

closely surrounds the path of the proton, so that the general shape of the particle orbit is visible in the external structure of the machine. During the course of its acceleration to an energy of 6,000 Mev, a proton goes around the track four million times and travels 300,000 miles. Fig. 4 shows a view inside the machine; at the right is the tunnel through which the protons go on their long journey, and at the left is a "crawl space" used for access to inner parts of the machine. When in operation, the interior

When the big cyclotron at Berkeley, the first machine anywhere to reach particle energies above 100 Mev, came into operation in 1947, the first experiment done was *mentioned earlier*, in which the high energy actually simplified the interpretation. Because of its historical interest and its simplicity, this will be described now. At that time the particles accelerated were deuterons, which are nuclei of heavy hydrogen *and* composed of a proton and a neutron rather loosely joined together; and the energy was 100 Mev. Fig. 5 shows a plan view of the experimental arrangement inside the cyclotron vacuum tank. The "doo" is the electrode that accelerates

the deuterons, which start at the center and move in expanding circular orbits until they reach the final orbit labeled "deuterons", and pass through a strip of metal labeled "thin target". In this target the processes we wish to study take place. When the nucleus of a target atom is struck by a rapidly-moving deuteron, the collision can be visualized something like that a globular assemblage of marbles (the nucleus) is hit by a dumbbell-like object (the deuteron). Both structures have a rapid and chaotic internal motion, and when they collide the resulting motions could be very complicated indeed.

However, one type of collision at high energy is particularly simple. Suppose that the deuteron comes in near the edge of the nucleus, so that one of its parts (for example, the proton) hits while the other part (the neutron) misses. Suppose further that the velocity of impact is so high that no great amount of internal motion takes place in the deuteron during the collision. Then, from the standpoint of the particle that missed, it is just as if its partner had suddenly been taken away, while the unstruck particle continues its motion as before. If it happens to be a neutron, which is unaffected by the magnetic field because it has no electric charge, it goes on in a straight line, labeled "neutron"; if it is a proton, its path is

in the plane

burst into a circle, like the ones labeled "protons".

Experimental observations show that both of these streams of particles occur, the protons being detected by proton-sensitive devices in boxes (labeled A, B, C) inside the cyclotron tank below the level of the deuteron orbits, while the neutron beam is found by detectors located outside the tank. Probably the most interesting fact about this experiment is that both beams have measurable spreads in direction and velocity, explained by the random internal motion present in the deuteron before it is broken up. A calculation of these spreads from previously known properties of the deuteron agrees with the measurements, giving one confidence in the correctness of the simple picture presented above. Of course not all nuclear processes are that easy to describe or understand.

Only a few years ago physicists spoke familiarly of "the fundamental particles of nature". Now they are a little apologetic in the use of that phrase; so many particles have been found that make some claim to being "fundamental" or at least to being cousins or uncles of "fundamental" particles that no one would know where to draw the line. I have prepared a table (Fig. 6) to show the present situation; the categories on the

left are not standard, but are convenient for the purpose of this article.

"Old fashioned" implies a time before about the middle of the thirties; "new" implies a time within the last half dozen years. The electric charges and masses are given in terms of the electronic charge and mass; the latter has an energy equivalent of 0.51 Mev.

The "old fashioned" particles are the nucleons, already mentioned before; the electron, which forms the outer parts of atoms, and its positively charged counterpart, the positron; the photon, which is just a fancy name for a light quantum; and the neutrino, the less said about which the better. (Some people like to call the "new" particles "strange"; it is hard to imagine anything stranger than a neutrino.)

The "ordinary" mesons form a family whose discovery, largely by studies of cosmic rays, occupied a number of years, and whose interrelations are now fairly well known. They are all unstable, decaying into other particles so rapidly that none of them last for more than a few millionths of a second; in performing experiments with them, all measurements must be made in the brief time between their creation and decay. They are of two basic kinds: π -mesons (π -mesons for short) and K -mesons (K -mesons for short).

Figure 2 combines a typical sequence of events involving positively charged

neutron. First, a proton, bombarded by high energy particles (it doesn't matter what kind of particles, the energy is the important thing) turns into a neutron, and a positive pion is created. This pion then decays rapidly in two stages, first into a muon and then into a positron, as indicated. The neutrinos produced as by-products of the decay are not seen or detected directly in any way, but their presence is surmised from certain arguments too involved to give here.

Figure 8 illustrates an event of this kind, as shown by the tracks left by charged particles in a sensitive photographic emulsion. This plate was exposed to a beam of high energy photons, produced by allowing electrons accelerated in the synchrotron to strike a metal target. At the left of the view, a photon hit a nucleus, and in the course of the resulting violence a positive pion was created (track going toward lower right corner) while, flying fragments of the ^{disrupted} nucleus produced the other tracks seen coming from that point. At the lower right, the pion stopped, then decayed into a muon (track going upward). At the end of the muon track the decay into a positron took place, but it does not show in this picture because the emulsion used was not sensitive enough to record the very faint track left by a positron.

When a neutral meson is made, the decay follows the scheme shown in Fig. 9, going in one stage with the production of two photons. Since photons make no tracks, a different method of detection is needed. All methods for detecting photons depend on the fact that they can collide with and set into motion electrically charged particles (usually electrons), and that the moving electrons do make tracks, activate golger counters, and so on. An ingenious experiment by which the reality of the two-photon decay was established is illustrated in Fig. 10. Off the picture to the right is a source of high-energy photons (the synchrotron); the two cylinders with axial holes (a made of lead, and serve simply to define a narrow beam of photons, which then go through the solid beryllium cylinder at the left; in this, the processes outlined in Fig. 9 take place.

The two decay photons are detected by two "telescopes" shown above the beryllium cylinder. Each telescope has a lead "converter" (cross-hatched block) and three sensitive elements (plain blocks). It gives a signal when an electron, knocked out of the converter by a photon, traverses the upper two sensitive elements, which are said to be connected "in coincidence". But the same signal would be produced by an electron which came directly

from the target cylinder; in order to prevent this, the sensitive element below the converter is connected "in anticoincidence", which means that if it gives a signal, the signal in the upper detectors is not counted. Finally the two complete telescopes are connected in coincidence, so that nothing is recorded unless they simultaneously detect two photons. The telescopes are mounted so that the angles α and β can be raised, and the way in which the counting rate depends on these angles gives information on the details of the decay process. This may seem like a very elaborate setup to study a relatively simple process, but the elaboration is really necessary because so many different things go on at once in a high energy bombardment that detection equipment must be specifically designed to sort out the process the experimenter wants to observe.

New Particles

Finally we come to the "new" or "strange" particles. These are not as yet well enough known to allow a systematic classification, but they are provisionally put into two general categories depending on their masses, as shown in Fig. 6. The lightest of the known K-mesons have a mass of about 1000, and therefore should require about 500 Mev to make. The hyperons probably contain nucleons as constituents, so that their whole mass does

not have to be created, since nucleons are already present in the particles that collide to make them. There seems to be good evidence, however, that neither K-mesons nor hyperons can be made singly, but that a single collision gives rise simultaneously to one of each, the energy required being such that one must work in the Bev region to study these particles effectively. The natural cosmic rays (all energies) and the Cosmotron at the Brookhaven National Laboratory (3 Bev) have been used for some time in this work; now the Bevatron has come into the field with particles having energies up to 6 Bev, and results from the combined attack are starting to come out.

It would be premature to discuss any results now, but I can show one example each of a K-meson (Fig. 11) and a hyperon (Fig. 12) made by the Bevatron. The K-meson is seen in a photographic emulsion; it comes in at the top right, is scattered once by a nucleus, and then stops in the lower left corner, where it decays into a pion, π , ^{which starts} _{then} starting out in a direction toward the upper right. The hyperon is found ^{in a} _{newly-developed} kind of detector, called a "bubble chamber", consisting of a chamber filled with liquid hydrogen; charged particles make tracks by causing bubbles to form along their paths. The event to look for is a pair of tracks forming a V pointing toward the right, with its apex nearly touching the vertical line,

and about a quarter of the way up from the bottom. These tracks were not made by the hyperon, but by a proton and a negative pion which resulted from the decay of the hyperon. The latter, since it was a neutral particle, did not make a track, but the inference that something did enter from the right and did decay at the apex of the V is inescapable. Bits of evidence such as this and the others discussed in this article are the raw materials from which physicists try to construct a reasonable picture of the elusive and complicated laws that govern the structure of matter.

Dec. 27, 1950

AAAS Convention at Berkeley
 E. E. McMillan

Figure Captions

Fig. 1 - The Synchro-Cyclotron at Berkeley.

Fig. 2 - The Synchrotron at Berkeley.

Fig. 3 - The Bevatron.

Fig. 4 - Inside the Bevatron.

Fig. 5 - Schematic plan of the stripping experiment.

Fig. 6 - Table of particles.

Fig. 7 - (no caption necessary)

Fig. 8 - Formation and decay of a positive meson, seen in a photographic emulsion.

Fig. 9 - (no caption necessary)

Fig. 10 - Schematic diagram of the apparatus for observing the decay of neutral pions.

Fig. 11 - A K-meson, seen in a photographic emulsion.

Fig. 12 - A Hyperon, seen in a photographic emulsion.

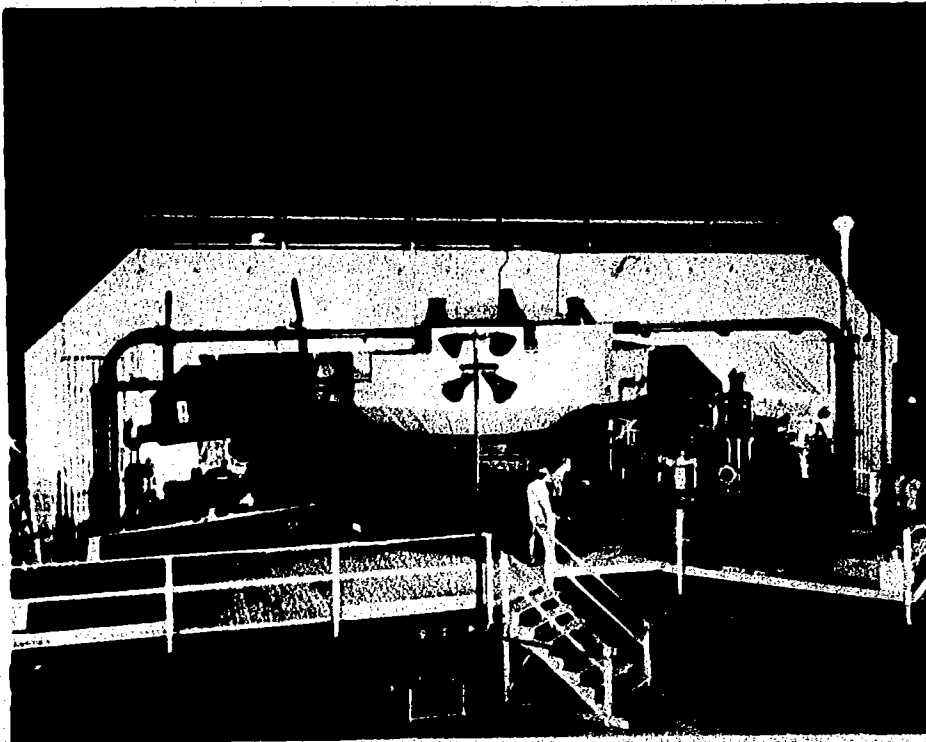


Fig. 1

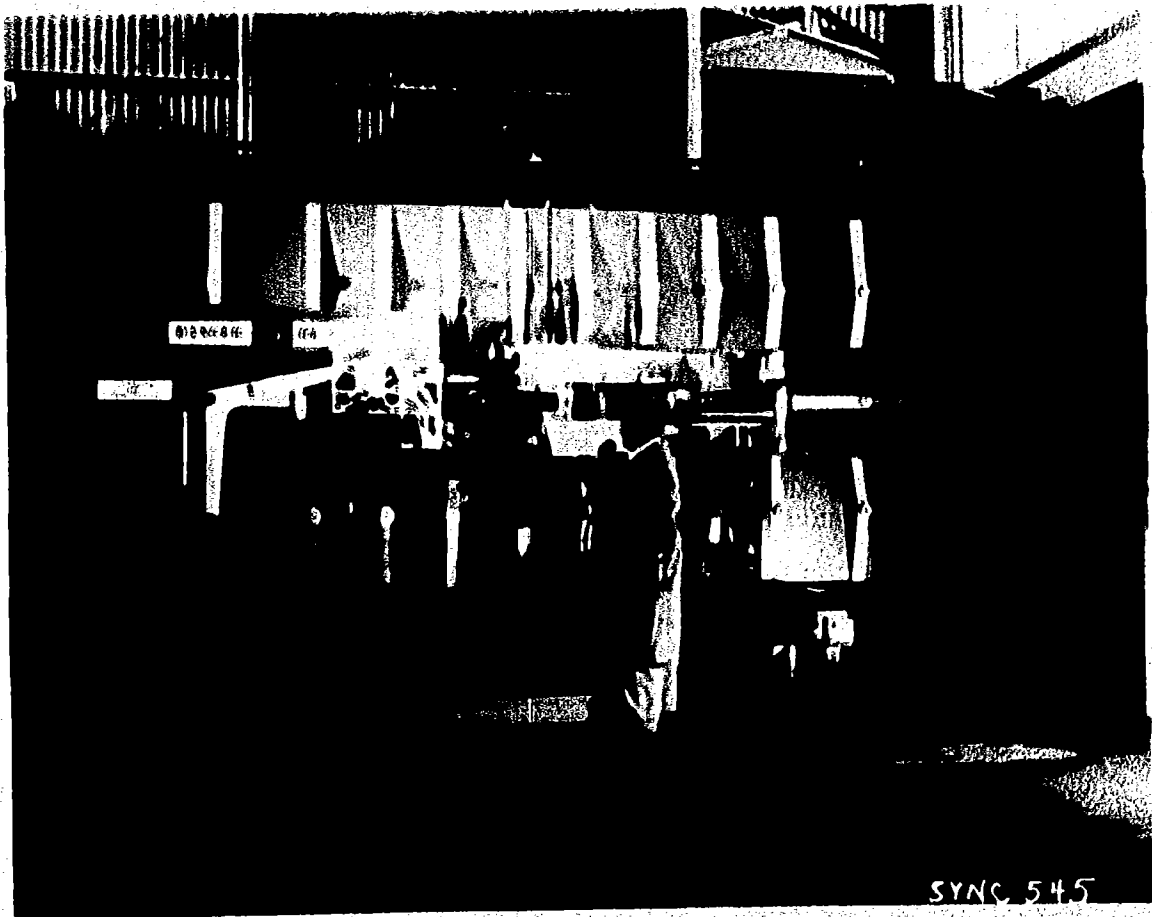


Fig. 2

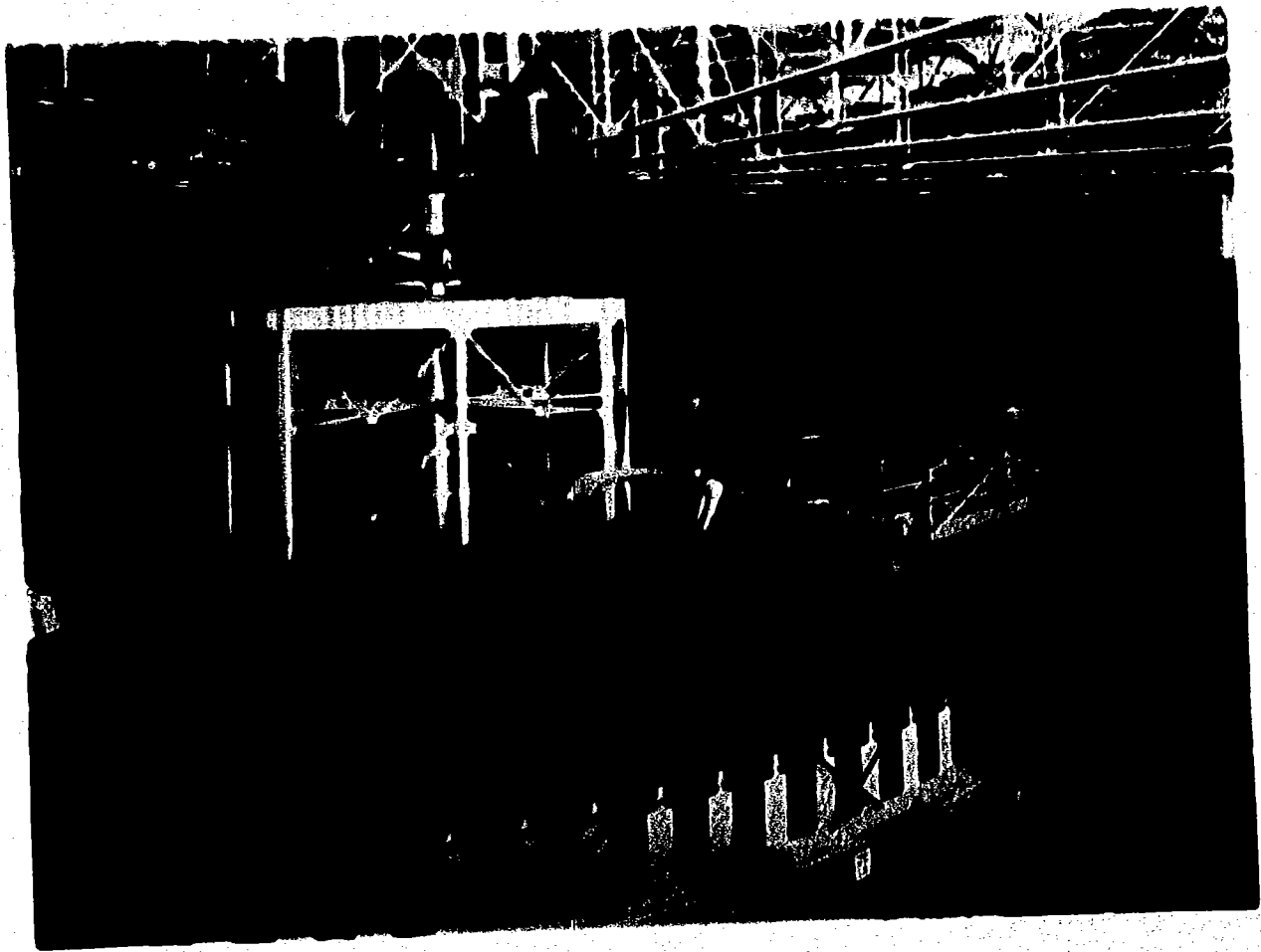
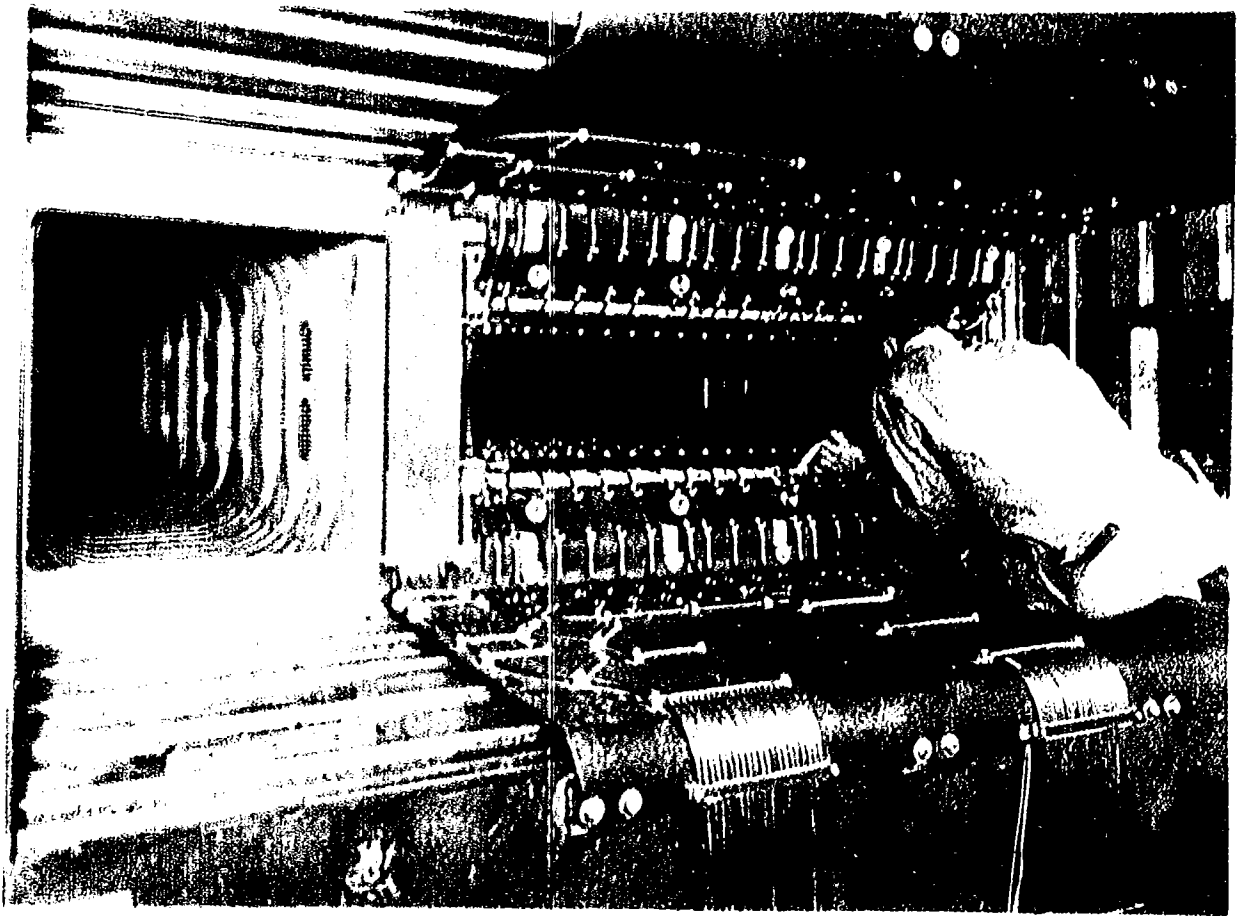


Fig. 3



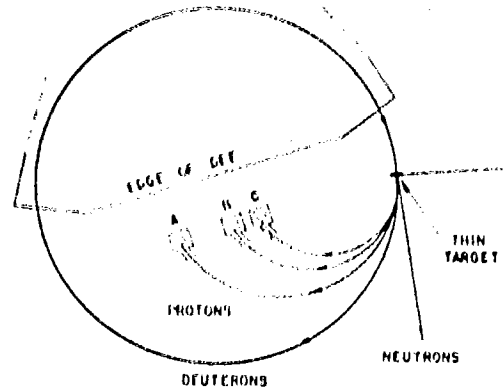


Fig. 5

	NAME	ELECTRIC CHARGE	MASS
"OLD FASHIONED" PARTICLES	NUCLEONS {	PROTON	1836
		NEUTRON	1839
	ELECTRON, POSITRON	-1, +1	1
	PHOTON	0	0
	NEUTRINO	0	0
"ORDINARY" MESONS	π -MESONS (PIONS)	{ -1, +1 0	{ 271 264
	μ -MESONS (MUONS)	-1, +1	207
"NEW" PARTICLES	K-MESONS (ABOUT 7 KNOWN)	{	MASSES BETWEEN PIONS AND NUCLEONS
	HYPERONS (ABOUT 4 KNOWN)		MASSES GREATER THAN NUCLEONS

Fig. 6

CAREER OF A POSITIVE MESON

CREATION:

PROTON (+ ENERGY) \longrightarrow NEUTRON + POSITIVE PION

DECAY, FIRST STEP:

POSITIVE PION \longrightarrow POSITIVE MUON + NEUTRINO

DECAY, SECOND STEP:

POSITIVE MUON \longrightarrow POSITRON + 2 NEUTRINOS

Fig. 7

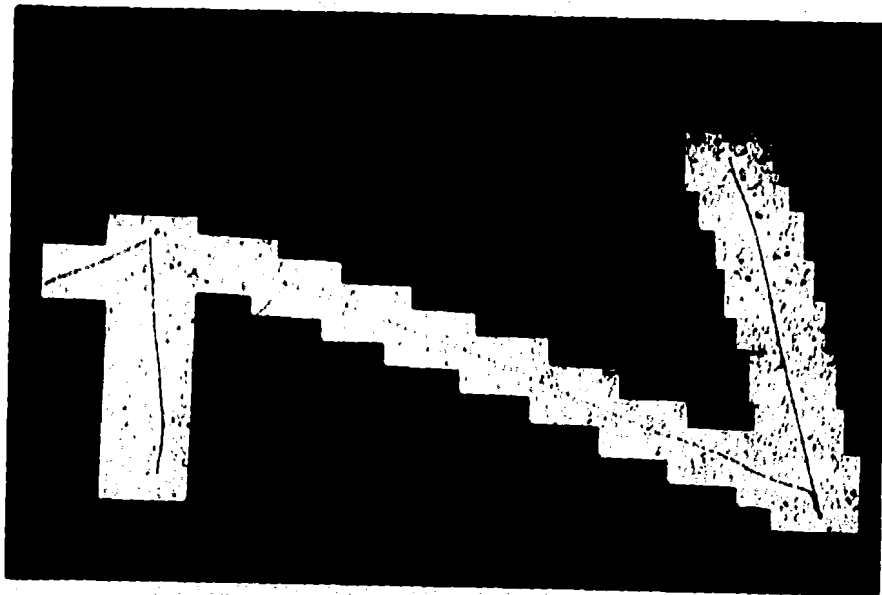


Fig. 8

CAREER OF A NEUTRAL MESON

CREATION:

PROTON (+ ENERGY) \longrightarrow PROTON + NEUTRAL PION

DECAY:

NEUTRAL PION \longrightarrow 2 PHOTONS

Fig. 9

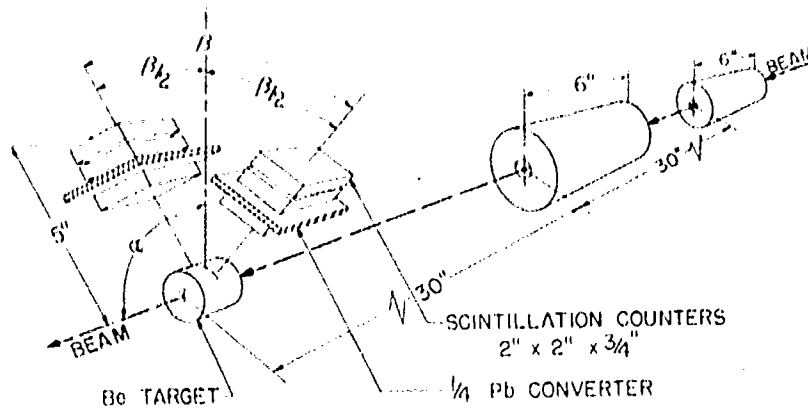


Fig. 10

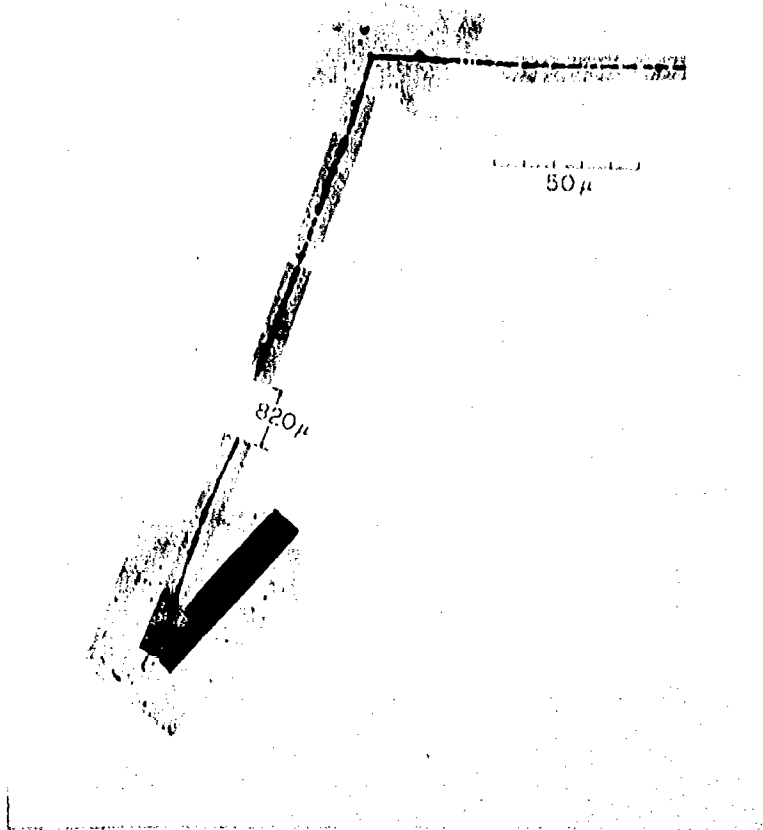


Fig. 11

0 0 1 0 1 3 0 4 0 1 8

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Fig. 12