How energy becomes matter ...

A first look at the world of particles

CERN

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A first look at the world of particles

(...with a supplement for those who would like to read further)

CERN
1986

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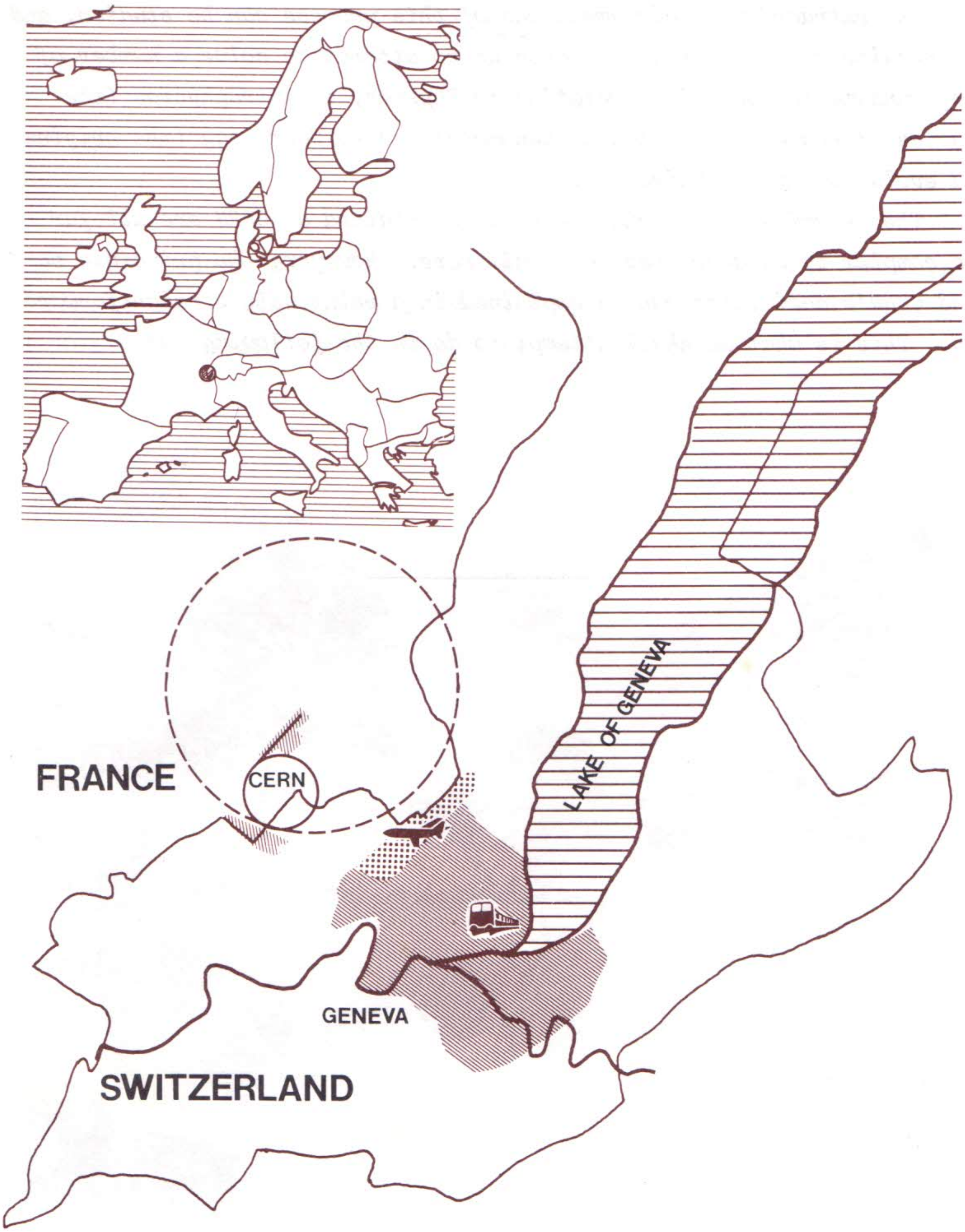
This booklet was designed and produced by Rafel Carreras in collaboration with Guy Hentsch.

CERN

European Laboratory for Particle Physics



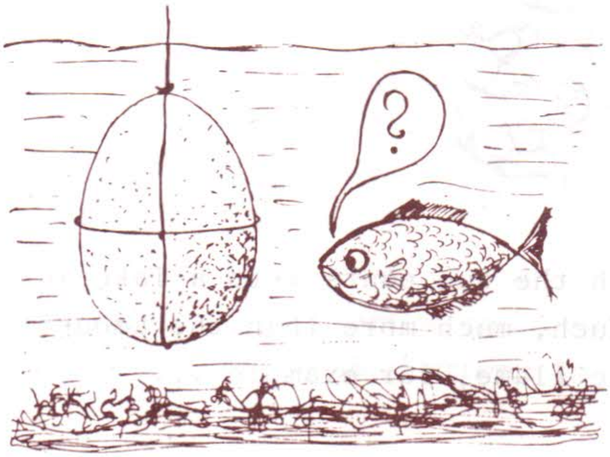
Just outside the city of Geneva is a large European research laboratory called CERN which lies partly in Switzerland and partly in France. The purpose of the laboratory is to study "Particle Physics", which really means what happens when energy becomes matter.

The extraordinary circumstances of this process can be studied, and the results of these studies enable us to attempt to solve a number of very fundamental questions relating to Physics, to Astrophysics (the physics of heavenly bodies and phenomena) and to Cosmology (the origins and evolution of the Universe).

The techniques used and the results obtained at CERN are all far too complex to be described in detail here. However, the principle behind CERN's activities can be explained in a relatively straightforward way. This is what we shall attempt to do in the following pages.

The amount of heat which the sun pours into a lake in a single day is enormous. Much, much more than the amount of heat given off by a candle flame, for example ...

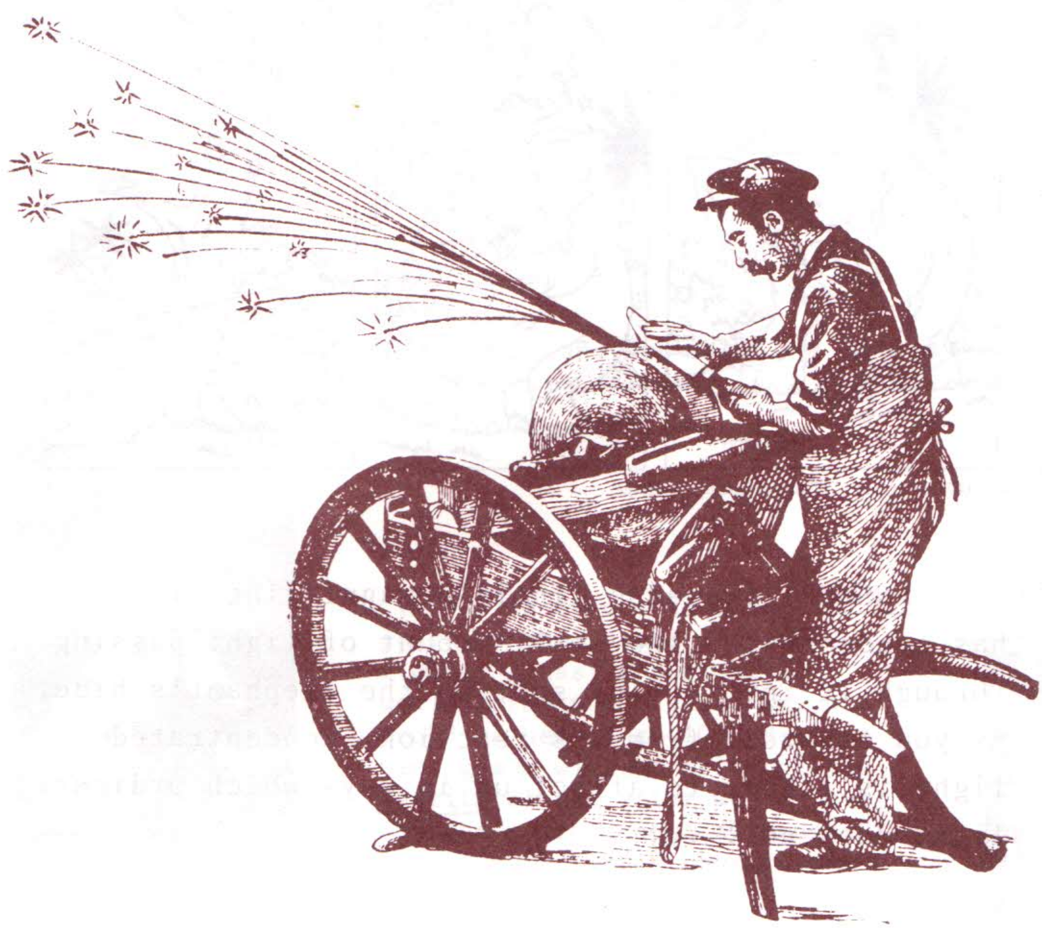
However, you will never boil an egg in a lake no matter how long you leave it, whereas you can do so with a candle in a few minutes.



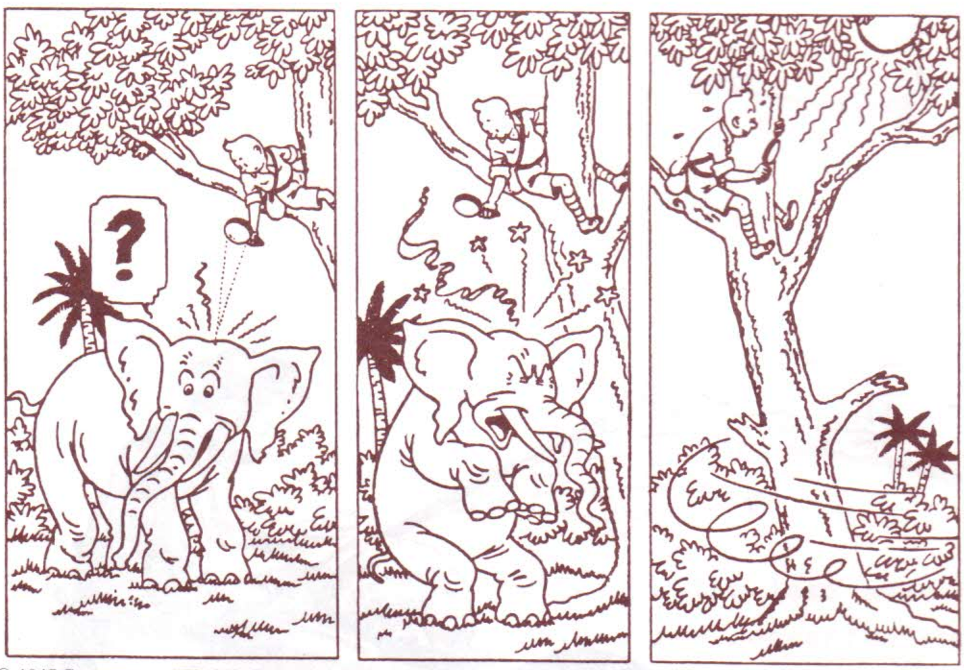
Why?

As the enormous amount of heat which the lake absorbs is diluted in a huge quantity of water, its concentration is very low. With the candle, it is a very different story. Although the quantity of heat produced by the candle is very small, it is concentrated in a very small area (the flame) and, since it is <u>concentrated</u> heat which causes the temperature to rise, it will cook the egg. It won't cook the egg very well, but it will cook it all the same, whereas nothing will happen in the lake.

Let's take another example: a knife-grinder. When he sharpens his knives, lots of tiny pieces of metal are ripped off the blade when it makes contact with the grinding wheel and fly off as sparks. These sparks may for a very short period of time have a temperature as high as 1000 degrees Centigrade. At such high temperatures, all objects produce light, not because of the quantity of heat they contain (a spark hasn't enough heat inside it to cook even a pea), but because the heat they contain is concentrated.



QUESTION: The total amount of sunlight beating down on the elephant's back is much greater than the few rays passing through Tintin's magnifying glass. So why does this small amount burn it, whereas it doesn't feel the rest of the sun's rays even through there are many more of them?



© 1947 Casterman, "Tintin in Congo" by Hergé

ANSWER: Because Tintin's magnifying glass has concentrated the small amount of light passing through it into a tiny spot on the elephant's hide. As you can tell from its reaction, concentrated light is likely to affect us in ways which ordinary light does not! ...

So we can see that it's concentration that counts. In everyday life there are many situations in which concentration is a more important factor than quantity:

● For instance, put twenty people on a kitchen table and there will be problems straight away! They will behave completely differently from the way they would behave if they were spread over a square kilometre. You don't have to be in a huge crowd to feel squashed!

● Let's take another example: you may think that a litre of water is a relatively small amount ...

... But if even this amount could be compressed into a liqueur glass, a sort of ice would form in the glass which could be heated to 1000 degrees Centigrade without melting! The quality of the water would have changed a great deal although its quantity would have remained the same.

Well, let's apply the same principle to the tiny amount of heat (or energy if you like) contained in the spark from the knife-grinder's wheel. What would happen if this tiny quantity of energy were to be concentrated in a volume millions of billions of times smaller than the smallest atom? The examples given remind us that by concentrating something we can radically alter its nature. You can well imagine, therefore, that if we concentrate energy into an extraordinarily small volume we can expect something really extraordinary to happen ...

?

... and we shall not be disappointed. For when so much energy is concentrated into such a tiny volume something very strange indeed, something incredible, almost miraculous happens: the energy of the spark is transformed into matter!

- What do you mean? Are you telling me that energy can be transformed into matter?

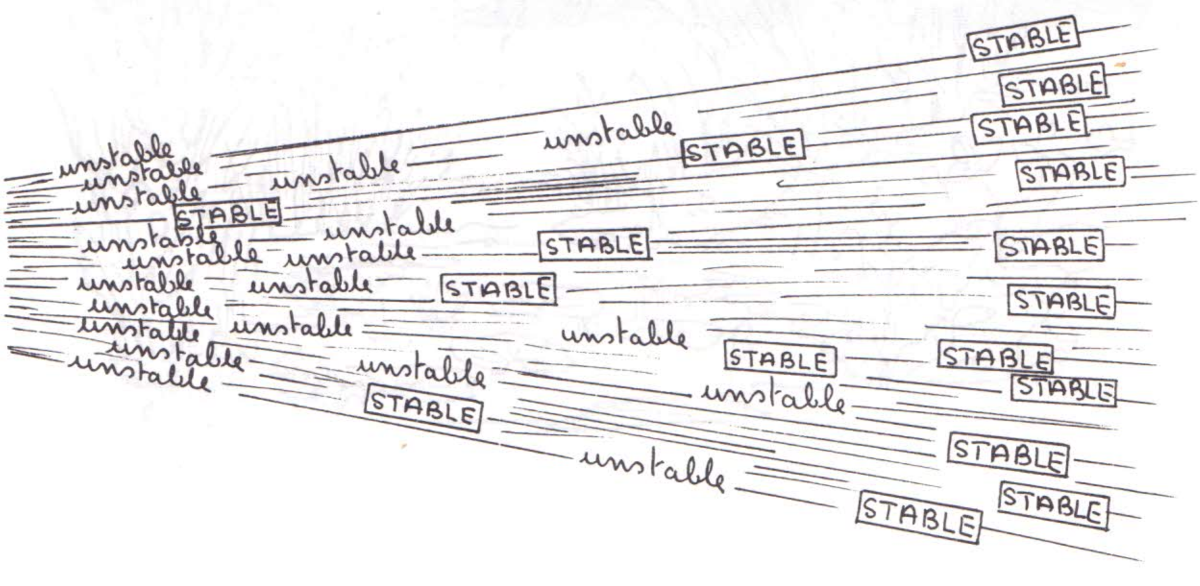
- Yes. Theory has demonstrated, and this has been confirmed by many experiments, that we must now regard matter as the compact, concentrated form in which energy sometimes exists.

But this process cannot be observed in everyday life. Nobody has ever seen energy being transformed into any quantity of visible matter, however small. There are three reasons for this:

1. Under normal circumstances, energy is insufficiently concentrated to produce particles of matter. It would need to be thousands of millions of times more concentrated.

2. In any case, particles produced from energy are so tiny that they are invisible to the naked eye.

3. And then again, they don't live long enough to come together to form visible objects since almost all these particles are very unstable when they are produced. Most of them "evaporate" immediately and become energy once again or disintegrate and produce other particles, which are often transformed in their turn into other particles, ... until, in the end, there are only stable particles left.



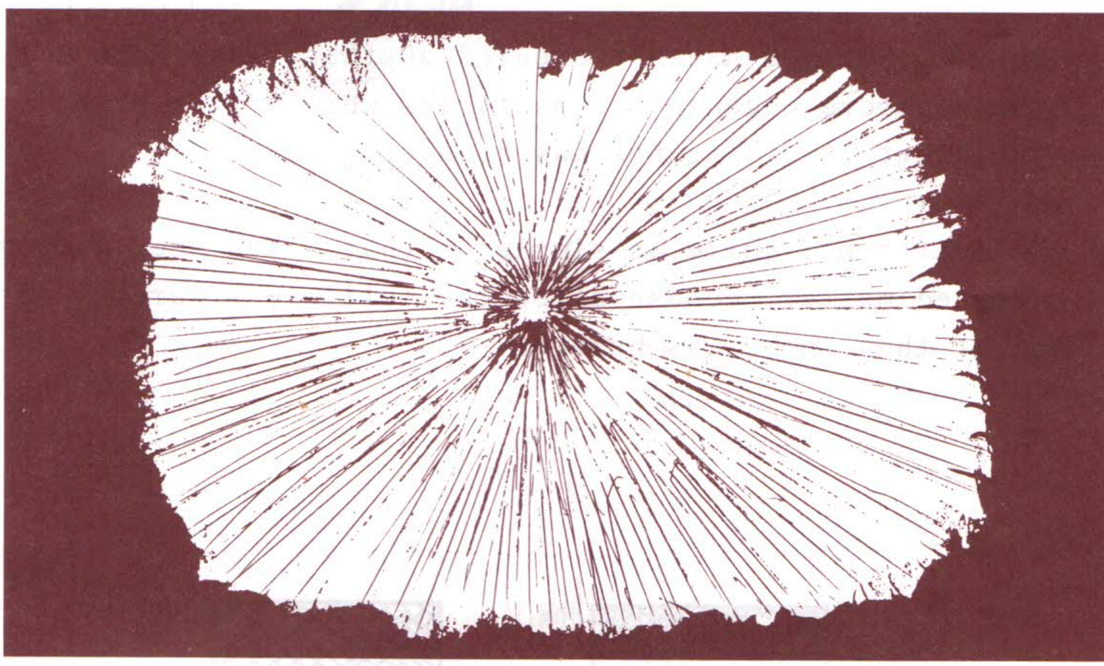
- So now these stable particles can form matter?

- Yes! Everything that we call "matter", i.e. minerals, vegetables and even living beings, is composed of stable particles. In fact only three types of stable particles are needed to construct the huge diversity of beings and things which exist in the world. What matters is the way in which they are put together. It's a bit like Morse Code which enables you to send any message you like by using different combinations of three basic signals: a dot, a dash and a blank space.

Since the beginning of the Universe, these same particles have never ceased combining and re-combining to form objects and living beings of seemingly infinite variety.

- So this means that the particles of which our bodies are composed are very old indeed?

- Yes, they were formed approximately 15 thousand million years ago when our Universe was created. It is thought that all this took place when a huge quantity of energy was suddenly transformed into incalculable billions of particles which, after many changes and transformations, finally stabilized and created the Universe as we know it and all the elements it contains.



We don't know where this enormous amount of energy came from nor how it suddenly came to be concentrated. But in specialized laboratories like CERN this process can be artificially induced on a very minute scale so that the process can be studied. Using large pieces of equipment known as accelerators to collide particles against each other, one can obtain, for very brief periods of time, sufficiently high concentration of energy to create matter ...

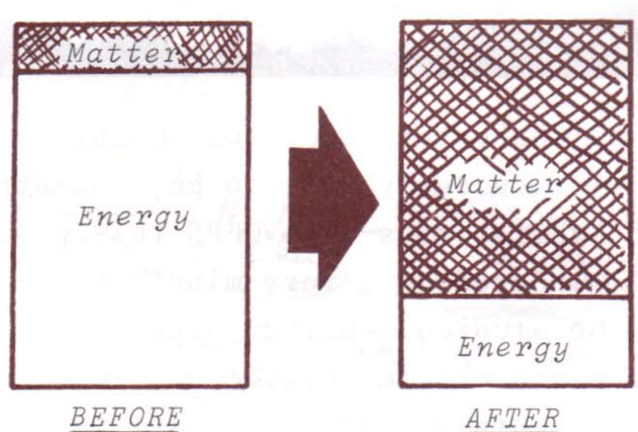
- Just a moment!

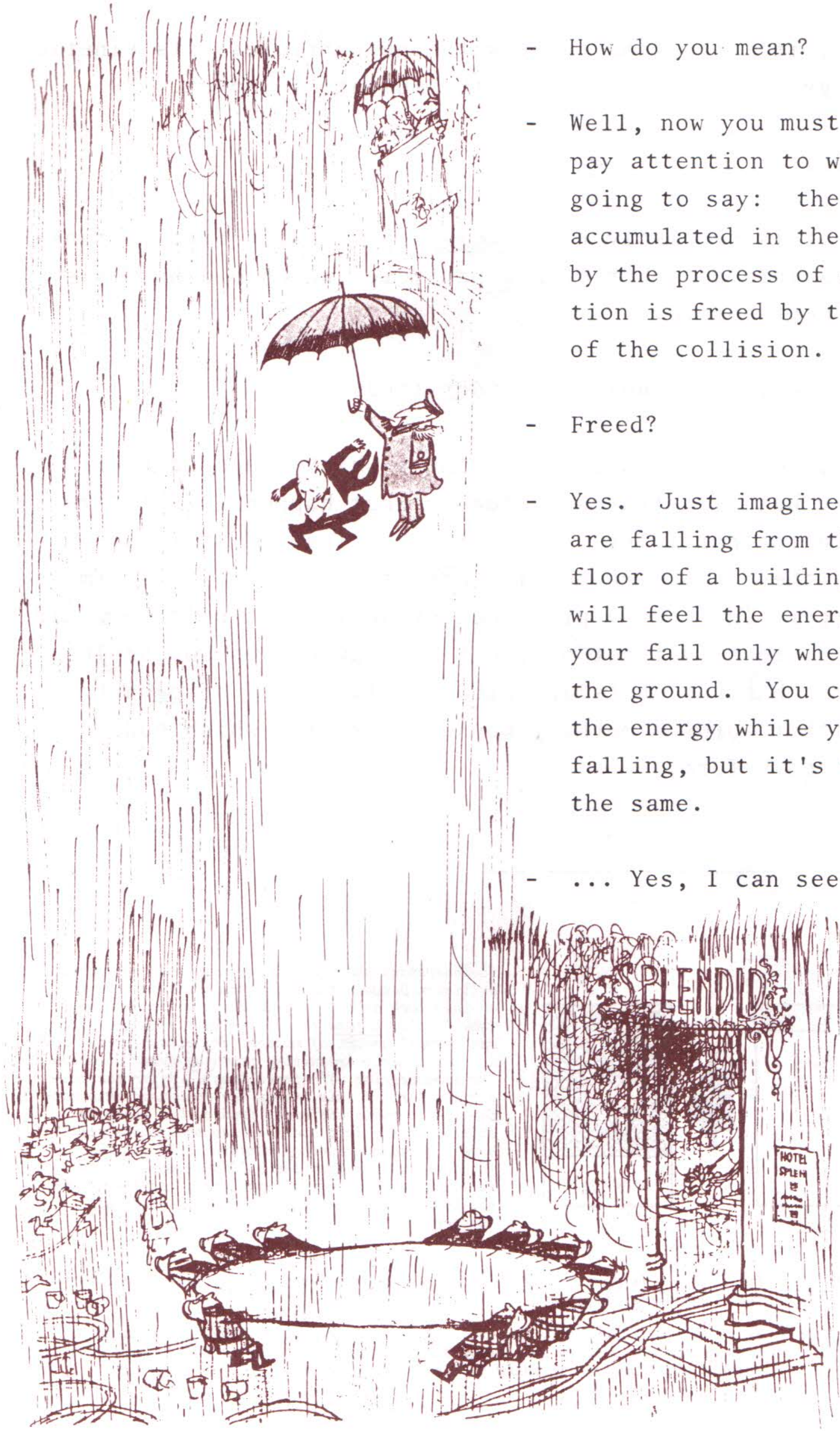
... How can you obtain such a large concentration of energy merely by accelerating particles or tiny objects?

- Because if you project an object at very high speeds you inject it with a very large amount of what is called kinetic energy. That's exactly what the accelerators do: the particles are accelerated almost to the speed of light and since the kinetic energy is applied to such a tiny object, it is tremendously concentrated. And when one particle meets another the energy is freed and transforms into matter.

- But ... but you haven't created anything that wasn't there before because the particles were matter right from the start. Nothing new has been created!

- Well it's not quite as simple as that. You see, we <u>have</u> created matter because after the collision there is more of it than there was before!





- How do you mean?

- Well, now you must <u>really</u> pay attention to what I am going to say: the energy accumulated in the particle by the process of acceleration is freed by the shock of the collision.

- Freed?

- Yes. Just imagine that you are falling from the sixth floor of a building: you will feel the energy of your fall only when you hit the ground. You can't feel the energy while you're falling, but it's there all the same.

- ... Yes, I can see that.

© 1962 Denoël, "Rien n'est simple" by Sempé

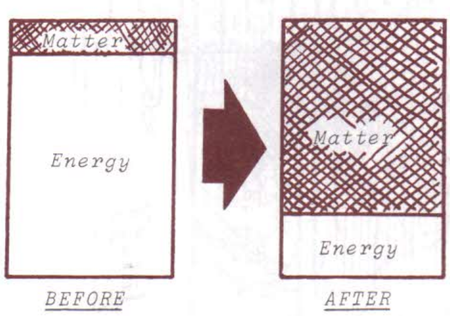
- Well, it's the same thing with the particle: its kinetic energy is only apparent at the moment of impact.

- I see.

- So, it is precisely <u>this energy</u> which, when freed, transforms into a number of new particles which did not exist a moment before.

- Ah, now I'm beginning to understand.

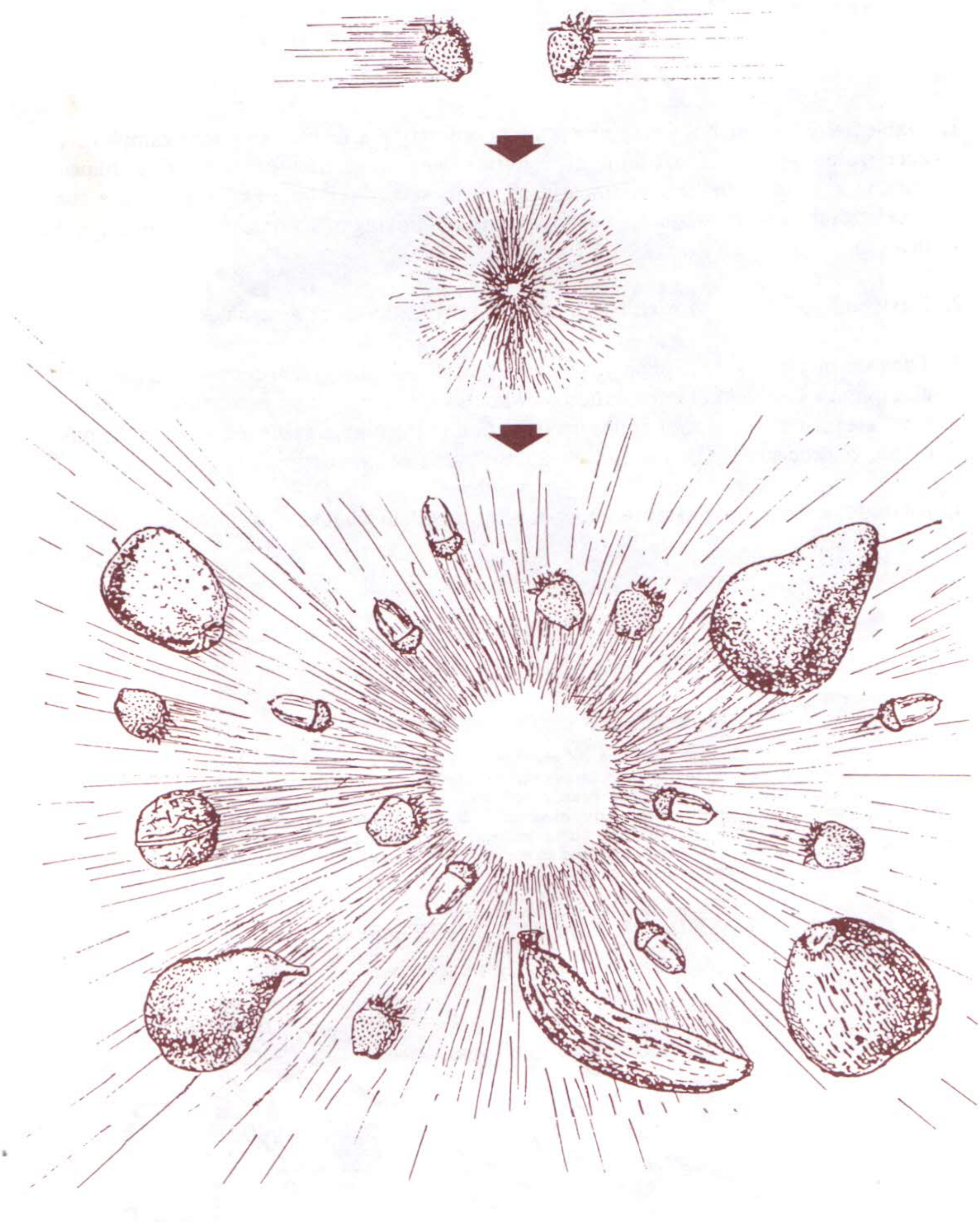
- Well, let's take a simple example which sounds rather silly but illustrates perfectly what happens. We'll replace the particles by two strawberries. Just imagine that these two strawberries were to collide with enormous energy. The energy produced for an instant of time would be so great that not only other strawberries but apples, pears, bananas, nuts and other fruits would be produced ... in other words something would be created which had not existed before.



To understand what is happening in this imaginary collision between the two strawberries, let's take another look at the diagram which we used on page 14 (see left). Before the collision took place there was a small amount of matter (the strawberries) and a lot of energy (resulting from the speed at which the strawberries were travelling). After the collision, part of this energy has condensed into matter (the various different fruits) but there is still a little left over because the fruits still have a certain amount of momentum. If all the fruits resulting from the collision were static, it could be said that all the energy of the original two strawberries had been transformed into "Matter".

QUESTION: *But would it in fact be possible to create particles (if not fruit) by colliding two strawberries together?*

ANSWER: *In theory it is perfectly possible. But with our present level of technical know-how we could never accelerate them fast enough. That is why we work with objects which are ten thousand billion times smaller!*



To return to our particles, we are now in a much better position to understand the general outlines of a CERN experiment:

1. Stable particles which are very abundant in ordinary matter (protons, for example) are accelerated by the application of electrical and magnetic forces in ring-shaped machines which can have diameters of up to several kilometres — these are **the accelerators.** Try and visualize what happens by thinking of a stone being spun around in a sling.

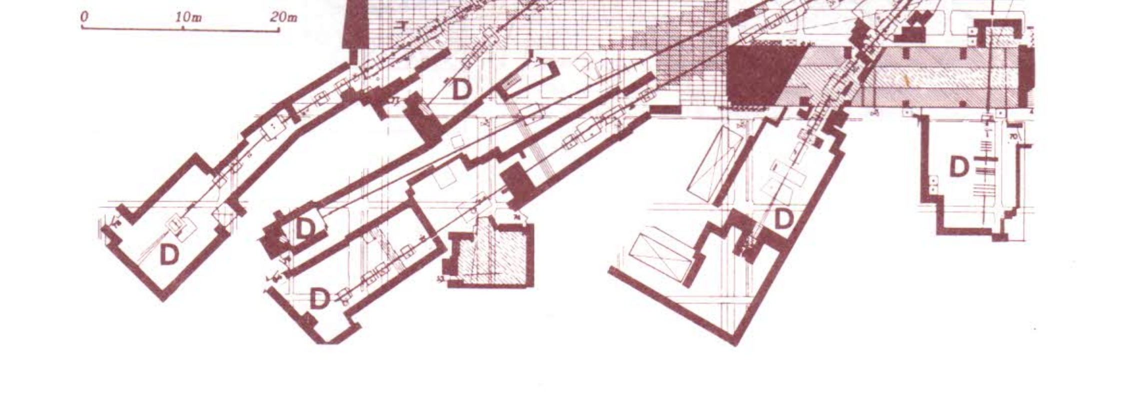
2. Next, collisions are organized which result in the creation of new particles.

3. Then the physicists try to observe what the particles do, using **detectors** which can only give a limited amount of information on what is happening. Using powerful **computers,** they later conduct a sort of police investigation to attempt to piece together all the bits of information so as to be able to see what the particles have done.

4. All that then remains is to try to understand and explain what has taken place...

Typical layout of an experimental hall

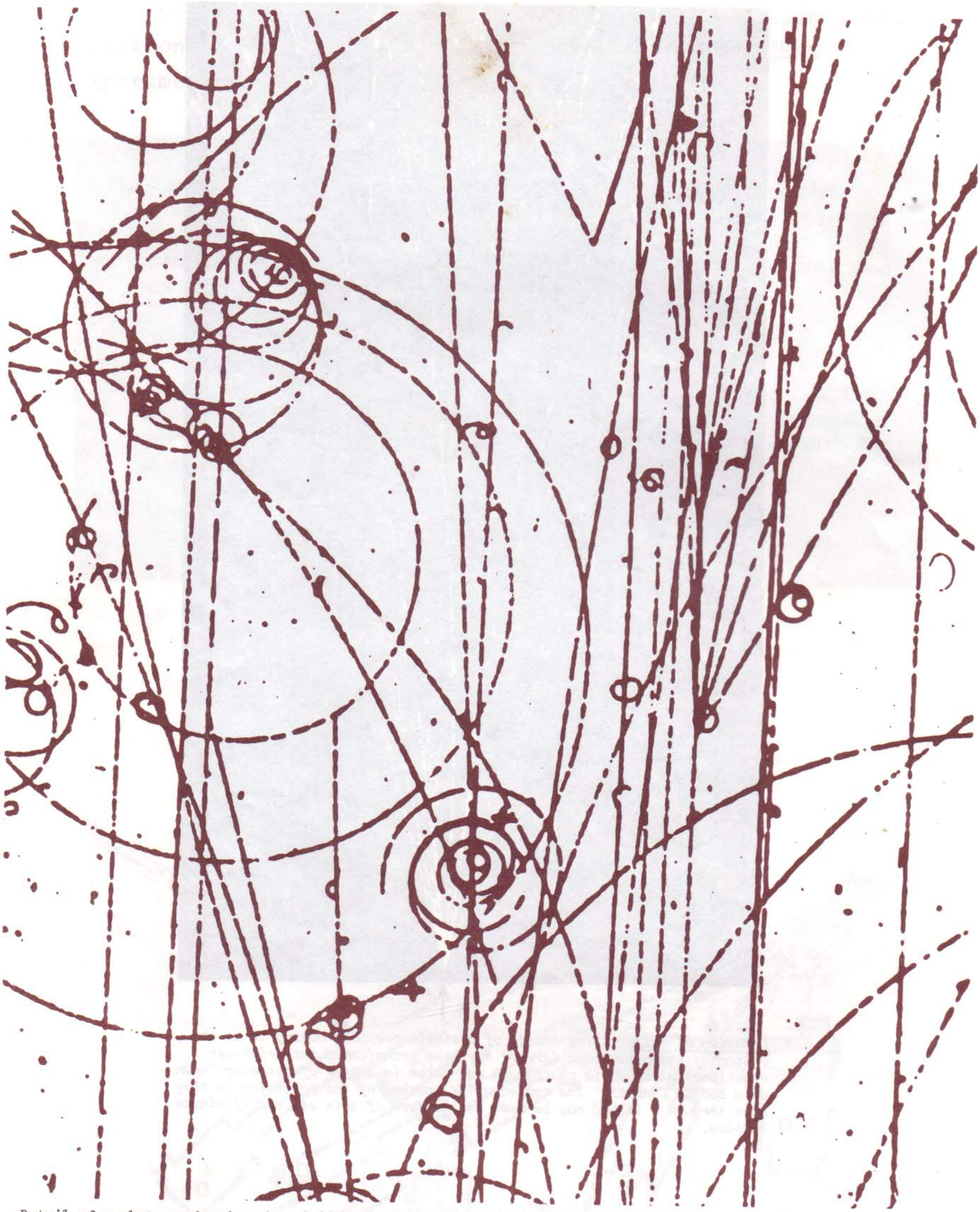
The arc of circle A is part of the "smaller" CERN synchrotron. The numerous rectangles inside it represent the magnets. The protons circulate in a tube which has been emptied of all the air. At two points (marked with arrows) the particles collide with a piece of metal and particles are produced from their energy. The particles we want to study are then filtered out and directed into experimental "corridors" where their behaviour is studied in the detector areas (D).



Here is a simple exercise for you to do:
Follow the paths of the six experiments.

Note the scale of the diagram!

<u>*Creation of matter:*</u> *The energy of a single particle coming in at the bottom of the photograph (arrow) has been transformed into eighteen other particles. This photograph was taken in a type of detector known as a BUBBLE CHAMBER. The trajectories (paths) of the particles as they pass through a liquid may be seen in the form of thin strings of minute bubbles.*

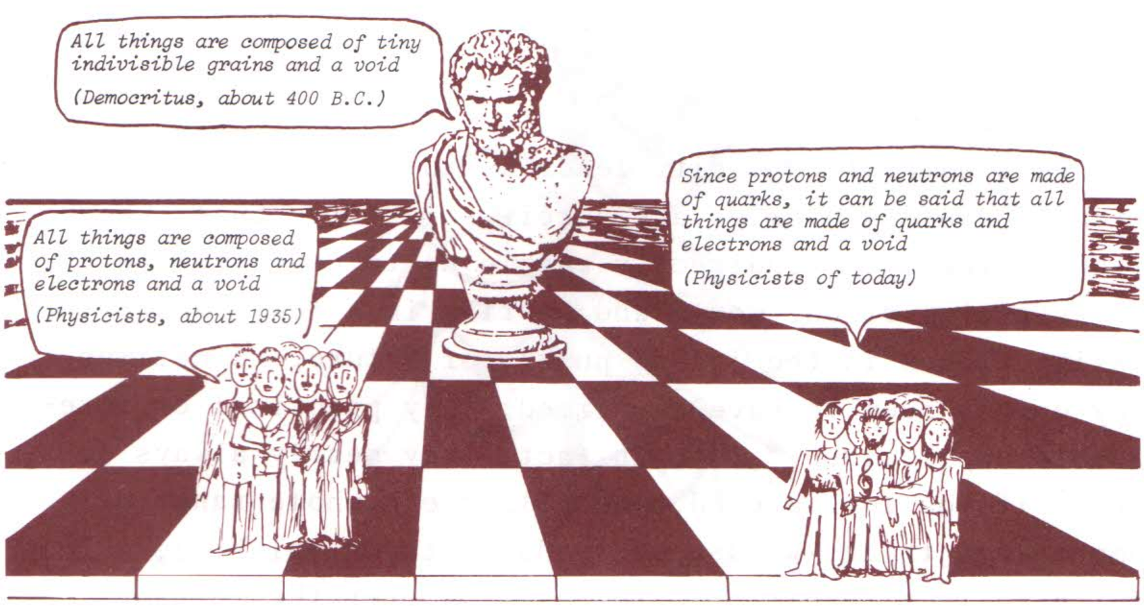


Detail of a photograph taken in a bubble chamber. The spiral trajectories are due to the effects of the magnetic field in which the chamber is placed. The faster the particles are travelling the less they will be affected by it. Thus, by measuring the curves you can tell a great deal about the masses and the speeds of the various particles. Other types of detectors, particularly electronic detectors, are also used.

- And where does that lead us?

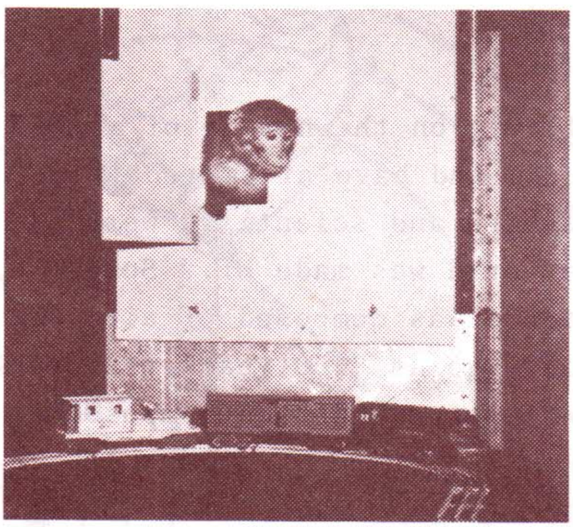
- To a better understanding of the composition and evolution of the Universe and of the structure of its smallest constituents (even in a sense, of its largest constituents), of the fundamental laws of Nature and why the Universe may one day come to an end ... although, admittedly, it is rarely easy to predict where our research will ultimately lead us.

For centuries men have reflected on the nature of matter and the laws governing the Universe and have attempted to define them. In Antiquity philosophers and scientists were already asking themselves what the world was made of. Some thought that everything in existence was composed of air, earth, fire and water ... As long ago as 2400 years the Greek philosopher Democritus argued that matter must be composed of different kinds of tiny grains.



Today, thanks largely to our accelerators, detectors and computers, we realize that in fact Democritus got very close to the truth. So you see modern pure research is trying to answer questions which man has been asking himself since time immemorial.

It is man's natural curiosity, his need to find out which is responsible for the kind of research work done at CERN and elsewhere. Everybody, including you, has a sense of curiosity. Even animals have it. Whenever there is a mystery you cannot help yourself - you have to try and solve it. This quest for knowledge is a fundamental need in living beings.



A photograph of a chimpanzee fascinated by a stationary electric train. All animals, even those far more primitive than monkeys, have a sense of curiosity. On occasions they are even prepared to risk their lives to satisfy it.

This natural curiosity leads us to make discoveries. Often, these discoveries are purely scientific ones, which either directly or indirectly enable us to have a better understanding of our world and to fill in a few more of the missing pieces in the jigsaw puzzle of Nature. Sometimes, they do not seem to have any immediately practical or foreseeable application. But, in fact, they nearly always do have: if you look around, you will see a whole range of commonplace things we use every day without thinking, which are the direct result of pure research over the years: radio, television and pocket calculators, to quote just a few examples. Fundamental research does not merely satisfy human curiosity, in the long run it also leads to practical developments which are of use in our everyday lives.

Another important factor here is that the scientists need new and specially designed machines and equipment to enable them to make further progress in the field of fundamental research. Sometimes these technical inventions bring breakthroughs in technology which are taken up by industry and in the end affect our daily lives.

- Can you give me an example of such an invention?

- Well, take the development at CERN of the positron camera, for example, which is proving to be a very promising alternative to the three-dimensional X-ray in biology and medicine. But don't forget that CERN is primarily concerned with pure research.

Perhaps the progress of particle physics research could be symbolized in the above way. Although not directly concerned with immediate practical applications, research makes use of various techniques (represented by the wheels) which have "spin-offs" in other fields. Here are a few examples of techniques which have resulted in such spin-offs: high-speed electronics, high-vacuum technology, special magnets, novel welding methods, very low temperature technology, etc ... etc ...

- But the "N" in CERN stands for nuclear, doesn't it? Is it really true that CERN experiments have nothing at all to do with nuclear power stations?

- Yes, that's quite right. CERN has absolutely nothing to do with nuclear power stations. This is not one of the purposes of the Organization as specified by the Convention, and there is no question, in the way it is organized or in its relations with the Member States which finance it, that CERN could ever be used for such activities.

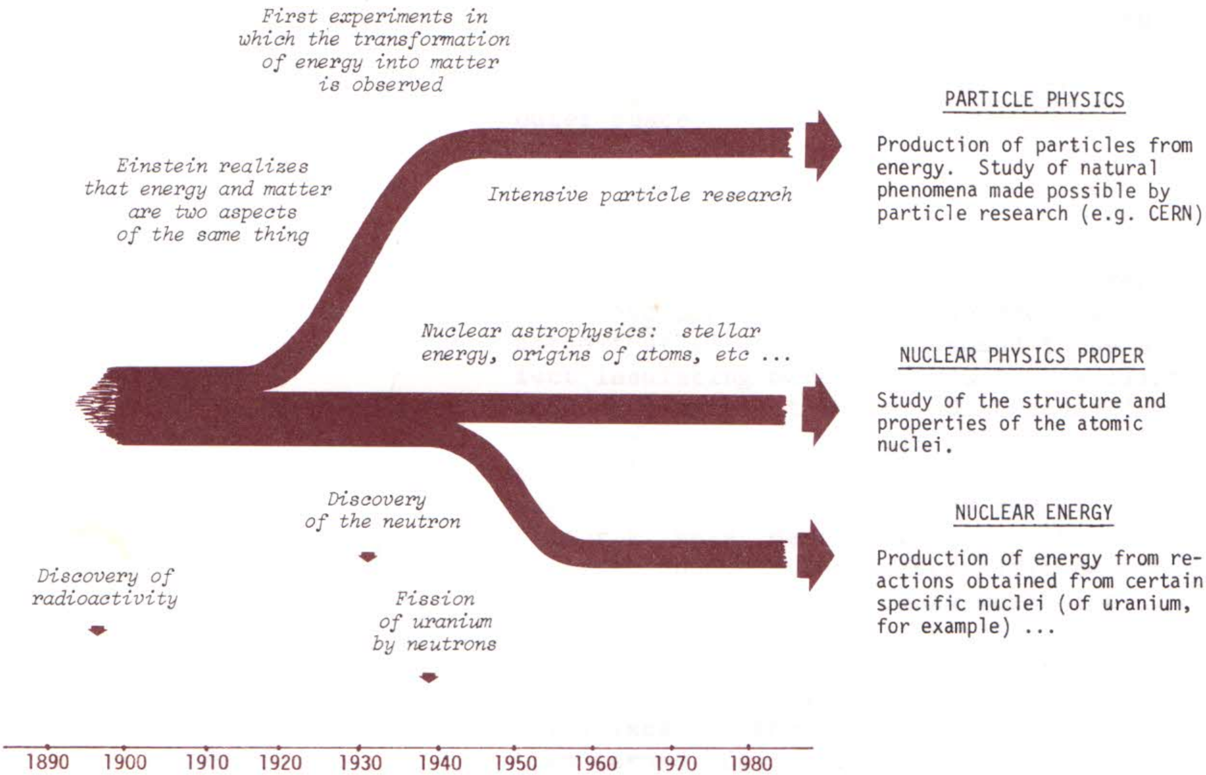
- But why then are CERN's activities and nuclear power stations both referred to as "nuclear"? What is the difference between them?

- The difference is that nuclear power stations produce energy from certain substances (uranium and plutonium) to provide heat and electricity, whereas at CERN very small quantities of energy are enormously condensed to produce matter. And, you know, the quantities involved really are small: no more than a milligram of matter has been produced in 25 years of experiments!

  So you can see clearly where the difference lies: nuclear power stations produce energy from matter whereas at CERN matter is produced from energy.

- I see, so it's exactly the opposite way round?

- Yes, in many respects it is exactly the opposite. And to make this point even clearer, let's just look at a diagram tracing the development of nuclear physics since the end of the last century.



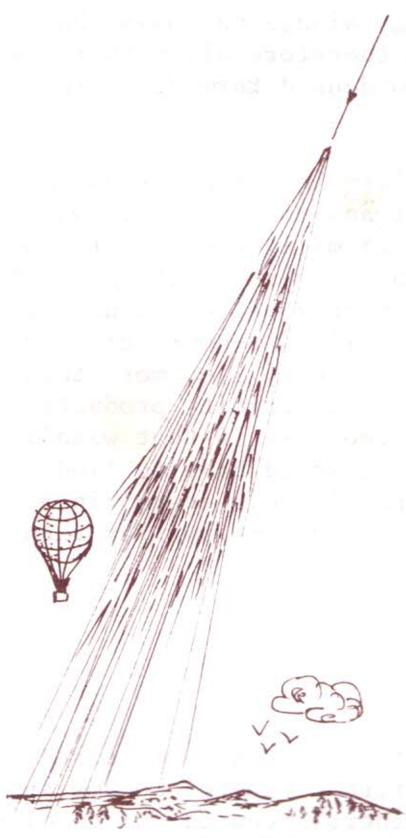
You probably still have lots of other questions to ask: scientific, technical or even economic, such as "Are all these experiments really worth their cost?"; sociological, such as "How does an international community of this type work?", or "What are the aims of the researchers who work there?"; or psychological, such as "Is our brain capable of grasping the laws which govern the behaviour of these extremely peculiar particles?" - and so on.

You may find the answers to some of your questions in the following pages. Some of you will need to look elsewhere in articles and books for more detailed information which will provoke other questions and encourage further reflection. Whatever you do, you will see that there is never an end to research. That is perhaps the source of its beauty ...

FOR THOSE WHO WOULD LIKE TO READ FURTHER

It all started with strange rays from outer space

Sometime about the beginning of this century a strange phenomenon was observed. It was noted that air, although assumed to be a perfect insulating material, was a very slight conductor of electricity. Some physicists began to suspect that this effect was due to particles coming from outer space. By ascending in a balloon, an Austrian physicist, Victor F. Hess, demonstrated that the air is a better conductor at higher altitudes than at ground level, a discovery which confirmed the hypothesis that the particles were coming from outer space. However, it was not until 1926 that this explanation was accepted by physicists and the strange phenomenon was then termed "Cosmic Rays".



Particles passing through the atmosphere are responsible for the conductive properties of the air. The higher the altitude (provided it is not too high) the greater the number of particles produced by a cosmic proton. At ground level there are many times fewer because a large proportion of the particles is absorbed in the atmosphere as they pass through it.

We now know that this phenomenon is due to particles, protons for the most part, travelling at very great speeds; but, however strange it may seem, we are still a long way from finding out where exactly these rays come from. During the thirties, however, they provided physicists with the first opportunity to observe the phenomenon of energy transforming into matter.

In a way, CERN is a laboratory where cosmic rays are produced artificially for study purposes. Whereas the physicists have no control over the quantity of particles coming from outer space, CERN's accelerators can provide beams of particles for research purposes in large, regular quantities and in optimum conditions. Nevertheless research is still continuing on cosmic rays because the energy of their protons is much greater than anything that can be obtained using accelerators on earth.

Einstein in 1905

Theory precedes experimentation

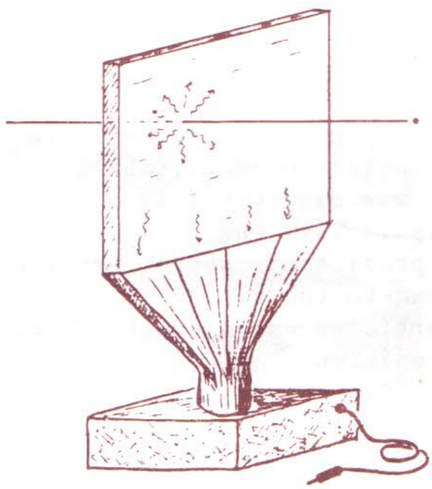
In the mid-nineteenth century, scientists had already worked out a fairly comprehensive picture of what energy was, but nobody had ever imagined that matter could be produced directly from energy. It was Einstein in 1905 who began to give cautious consideration to this idea. He discovered that in certain circumstances energy behaves as if it had mass. In the course of time it was proved not only that energy always has mass, but that all mass, and therefore all matter, may be regarded as a condensed form of energy.

Einstein's famous formula $E = mc^2$ says exactly that, but in a neat and more accurate way. Thus, for example, 25 million kilowatt-hours "weigh" one gram and conversely if you wanted to try and produce matter you would need to condense 25 million kilowatt-hours of energy to obtain 1 gram of matter, i.e. more than Switzerland's entire electricity production over a six-hour period. As if that wasn't difficult enough, you would have to find a way of concentrating all this energy in a manageable form into a volume smaller than that of a microbe!

The first detectors

As our knowledge of cosmic rays increased, and as the real nature of energy became apparent, the researchers invented and developed a whole series of instruments and devices for observational purposes.

Before 1912, the only means of studying cosmic rays had been to measure the conductivity of the air, a method which did not provide much information on the behaviour of the cosmic particles themselves. After all, at that stage, the physicists were not even aware that cosmic rays were really particles. The first significant step forward came with the development of a counter which emitted an electric signal whenever the particles entered it. This device provided more precise definition of the particles in time and space.



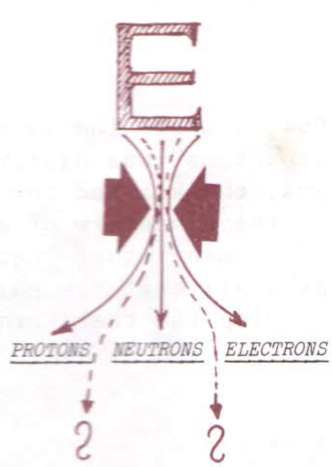
An example of an electronic detector: the scintillation counter. When a particle passes through it, it emits a small amount of light which in turn triggers an electric signal.

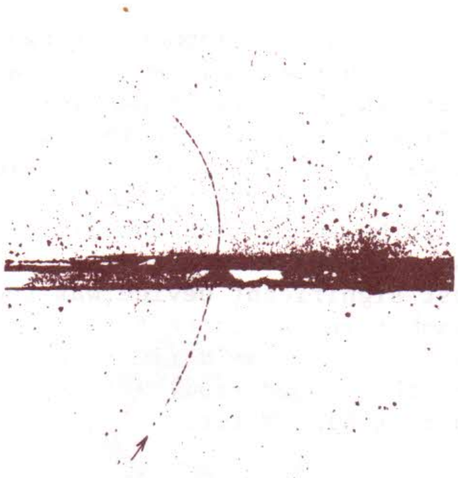
But it was not until the development of two new techniques, the photographic emulsion and the cloud chamber, that the first particle physics discoveries were made. In the case of emulsions it was noted that, after development, the passage of the particles through the emulsion could be seen, with the aid of a microscope, as a series of black dots. However, the most significant device was the famous cloud chamber in which the trajectory of a particle was observed as a fine line of fog, rather like the vapour-trail left behind by a jet aircraft at high altitude.

Photographic emulsions, cloud chambers and counters (the last two often used in conjunction) were to remain the principal tools of research for particle physics from 1928 until as recently as the early 1960s.

The particle list gets longer

By 1930, two fundamental particles, the positively charged proton and the negatively charged electron, had already been identified by means other than studies relating to cosmic rays or to the condensation of energy into matter. An attempt was then made to describe the structure of matter using these two elementary particles. This proved very difficult until the discovery of the neutron in 1932. Now that the proton, the electron and the neutron had all been discovered, it proved possible to understand virtually all the properties of the atom. Did this mean, therefore, that when energy condenses into matter it converts only into these three particles?





This track is famous in the history of physics: it is that of the first anti-electron ever detected (in 1932).

Far from it! In 1931, a British theorist, P.A.M. Dirac, predicted the existence of an inverse electron, the anti-electron or positron as it is now called, which unlike the ordinary electron would have a positive charge. He had no sooner predicted its existence than it was discovered. In 1932, to be precise, a track which could only be that of an anti-electron was discovered in a cloud chamber photograph. This was followed by a whole series of predictions and observations which were to lead to the discovery of phenomena and of particles whose existence nobody had ever predicted.

In 1930, Pauli predicted the existence of a neutral particle (the neutrino) with the characteristic of being, amongst other things, virtually undetectable. Nevertheless, it was detected in 1956. (By the way, CERN possesses the most advanced installation in the world for the production and study of neutrinos).

A cosmic proton has collided with a proton at rest in a photographic emulsion. A jet of 28 pi mesons produced from the energy of the incoming (incident) proton can be seen.

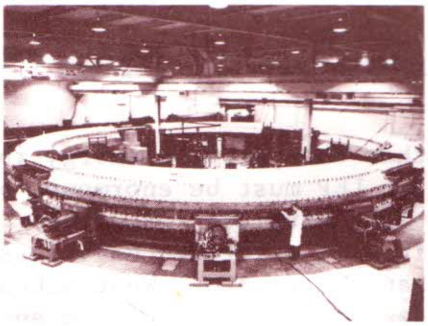
In 1932, a Japanese physicist, Hideki Yukawa, predicted the existence of an unstable particle, the "pi meson", which was discovered in 1947. It was during the search for the pi meson that the physicists discovered another unstable and peculiar particle, the muon, which is a type of heavy electron.

Between 1947 and 1964, a whole family of "heavy and unstable protons" was discovered: the lambda, the sigma, the ksi and the omega. This was followed by the discovery of another "heavy electron" and of many other "heavy protons" and "mesons", all unstable particles which are produced during the transformation of energy into matter.

The advent of accelerators

At the beginning of this century, proton and electron accelerators already existed, but the particles could not be endowed with sufficiently high energies to produce matter from collisions. It was not until the 1950s that an accelerator was developed capable of attaining the energies required. In 1954, at

Berkeley in the United States, a successful attempt was made in a synchrotron called the Bevatron to induce protons to produce various other particles, especially anti-protons and anti-neutrons, by accelerating them with electric forces and guiding them with powerful electromagnets.



One of the first large accelerators to be built after the Second World War: it had a diameter of approximately 20 metres and the energy of the accelerated protons was about 3 GeV.

The existence of these particles had been predicted as far back as the early 1930s, - which clearly shows that the two essential qualities for this type of research are endless patience and perseverance! But it also requires ever larger accelerators if progress is to be made. The first accelerators measured a few centimetres only or at most a few tens of centimetres. Later, larger ones were constructed measuring several metres or, as in the case of the Berkeley synchrotron of 1954, several tens of metres and weighing more than 1000 tonnes. CERN's "little" synchrotron, commissioned in 1959, has a diameter of 200 metres. The large CERN synchrotron has a diameter of 2.2 kilometres, however, while the future LEP accelerator, destined for electron and anti-electron collisions, will have a diameter of more than 8 kilometres! And so the story goes on.

Why do accelerators have to be so big?

A view inside the tunnel of CERN's Super Proton Synchrotron (SPS). This accelerator has a diameter of 2.2 kilometres and achieves a proton energy of 400 GeV.

At this point, one possible source of misunderstanding must be cleared up straight away: an accelerator with a diameter of 8 kilometres does not have to be housed in a huge building. In the case of the future LEP accelerator, for example, the machine will be installed in a deep underground tunnel with a width of between 3 and 4 metres.

The main reason why proton and electron accelerators need to be so large is that the magnets used to draw the particles along and keep them on course have a limited magnetic strength. The smaller the circle, the greater the strength of the magnet must be to curve the trajectory of the particles. This inevitably means larger circles, rather in the same way as the curves on motorways must be of larger radius to ensure that cars travelling at 80 miles per hour do not spin off the carriage-way.

The problem becomes even more acute in the case of electrons, which have a tendency to lose energy in the form of emission of light as the curve of the trajectory increases. This is why the LEP machine, which is to accelerate electrons, has to be so large.

<u>We still cannot compete with a mosquito</u> ...

One would think that the particle energy in a huge machine like LEP must be enormous, but this is not so. The particles circulating in the largest machines in existence have less kinetic energy than a mosquito! What makes all the difference, however, is that in an accelerator the particles are very small indeed and their energy is extremely concentrated. If two mosquitoes collide, no new particles are produced, whereas when two protons or electrons with the energy of a mosquito collide they do produce other particles.

It is time to explain the significance of "thousand million electron volts" - giga-electron-volts or GeV (pronounced JEV) - a term which may be confusing. We say, for example, that such and such an accelerator accelerates particles to 30 or 140 GeV. The GeV is one of the units of energy used in particle physics and represents approximately the total amount of energy which must be condensed to form one proton. (The Super Proton Synchrotron at CERN endows protons with an energy in excess of 400 GeV.) "Giga" means a billion, i.e. a thousand million; in other words, the energies used in research work are of the order of several billion electron volts, or even some hundred times higher. That sounds a lot, but in fact, in everyday terms, it is really quite a small amount; and in any case you certainly must not think of this energy in terms of ordinary electric current of equivalent voltage. An electron volt is so tiny that even a billion (a thousand million) electron volts is an almost negligible amount: a pencil falling from a table for example, possesses an energy of several hundred million billion electron volts. So, to sum up, the really extraordinary aspect of particle acceleration is not the amount of energy imparted to the particles but the minute size of the objects in receipt of all this energy.

1 GeV =
1 thousand million (or billion) electron volts
=
The energy needed to create a proton
=
A thousandth of the kinetic energy of a mosquito in flight

Thus, although several hundred billion electron volts would have a negligible effect on everyday objects, they can have a surprisingly significant effect on protons or electrons, as we saw in the first part of this booklet, and the energies involved are sufficient to bring about the transformation of energy into matter and create particles. Of course, you can see from the size of the accelerators that the processes involved are not quite so straightforward as this simple analysis would suggest.

We are made of isolated "dots" wandering around other "dots" in groups of three

The most fundamental particles are very difficult to visualize, but one can regard them as "points" or "dots" of matter with a precise mass, which have so far eluded all attempts to measure them.

What we do know is that when energy condenses, it is transformed into these "dots". There are two types: the type that always exists independently of others (the electron, the muon or the neutrino, for example) and those which automatically group together (the quarks).

When quarks group together in pairs they become mesons, which are always unstable. When they group together in threes, they produce the familiar particles, like the proton and the neutron, or others which are unstable, such as those belonging to the family known as the "heavy protons".

The sky
the Earth
the wind
the seas
trees
animals
human beings
all things
are made of
quarks **u**
quarks **d**
electrons
and a void

If we confine ourselves to the stable particles, those which constitute our own bodies and the world around us, the list of basic constituents is very short:

- the "points" which stand "alone": the electrons,

- the "grouped points": the u and d quarks,

and that's all!

<u>The basic constituents of a cow</u>

We cannot actually make a cow from electrons and u and d quarks, of course, but we can imagine how we would set about it.

1. First of all make a proton by taking two u quarks and one d quark. Repeat the operation until you have a large stock of protons.

2. Then make a large quantity of neutrons from combinations of one u and two d quarks.

3. In addition to a good supply of protons and neutrons, you will need a good stock of electrons (in fact, you need the same number of electrons as protons).

4. Next make the atoms: for a cow you will need mainly carbon, oxygen, hydrogen and nitrogen atoms.

PROTON

NEUTRON

Here is the recipe for hydrogen: take a proton and release an electron near it. The electron will circulate more or less around the proton. In any case, it will remain in the vicinity of the proton.

NUCLEUS OF A CARBON ATOM

Comprising 6 protons and 6 neutrons. At this scale the electrons would be located several hundred metres from the nucleus

Recipe for carbon: take 6 protons and 6 or 7 neutrons and keep them in contact with each other for a few moments so that they form a solid ball. Then release 6 electrons which will begin to gravitate around it.

Repeat the same procedure for the nitrogen, this time taking 7 protons, 7 or 8 neutrons and 7 electrons. Similarly, to produce oxygen atoms you will need 8 protons, between 8 and 10 neutrons and 8 electrons. You will also require calcium and phosphorus atoms for the bones, iron for the haemoglobin of the blood and so on, all requiring different combinations of protons, neutrons and electrons.

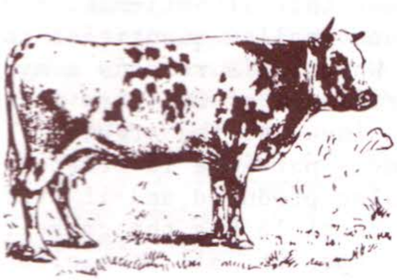
A MOLECULE

Consists of a combination of atoms of various kinds.

5. Assemble the atoms in molecules. For water you will need 2 hydrogen atoms and 1 oxygen atom. For certain other molecules you may need to assemble together many hundreds and thousands of atoms.

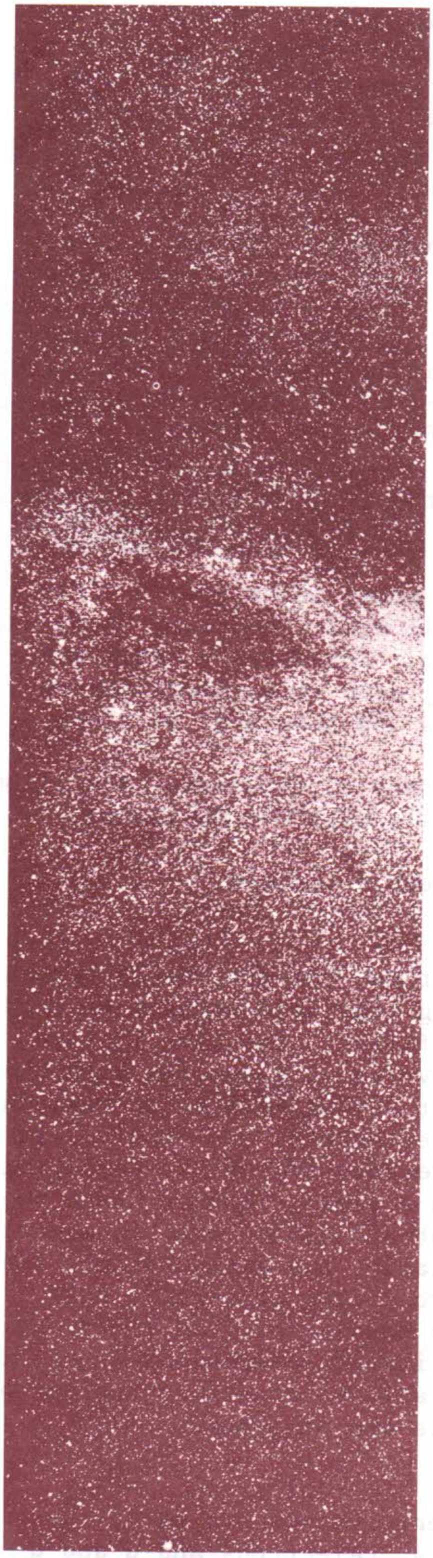
6. Build a few tens of thousands of millions of living cells with the molecules.

7. Finally, assemble the cow.



Of course, in Nature, the process of growth takes a very long time, and we have omitted one other vital factor: the time it took for the cow to evolve as a species with the power, like other living beings, of reproducing itself. Nevertheless, our "recipe" is an accurate representation of the composition of a cow, and in a similar way of human beings for that matter, at the most fundamental level. Incidentally, the extraordinary feature of the reproduction process is that under favourable conditions, the living being can "re-create" itself independently - as if a computer were able to construct another of its kind from its own programme.

But the basic constituents are still the "points" or "dots" (electrons and u and d quarks) which, like all those constituting our planet and its inhabitants, are the result of a condensation of energy which occurred between 10 and 20 thousand million years ago.



A small part of our galaxy. The distances between each of the white dots, which are in fact suns, are enormous, but even our whole galaxy is only a tiny fraction of the Universe.

And yet the world exists

Theory has predicted, and the experiments carried out at laboratories such as CERN have confirmed, that every particle has its "opposite" or anti-particle.

Both quarks and electrons have their respective anti-particles. The first fascinating characteristic of this phenomenon is that when a particle encounters its anti-particle, they destroy each other and their matter becomes pure energy once again (in the form of light, for example, or more frequently as rays of the X-ray type). Another aspect of the phenomenon is that when energy condenses into particles it always creates the same number of particles as anti-particles. Since both types of particles have approximately the same properties, it is not difficult to conceive of the existence of an "anti-world" consisting of anti-atoms, anti-molecules, anti-cells, anti-cows and even of anti-planets composed of anti-protons (2 u anti-quarks and one d anti-quark), anti-neutrons (one u anti-quark and 2 d anti-quarks) and anti-electrons.

In short, anti-particles ought in principle to combine to form masses of anti-matter. Do such quantities of anti-matter exist in the Universe? No specific answer has yet been found to this question. However, it is now generally agreed that if anti-matter does exist, it is in much smaller quantities than ordinary matter. Why? This remains a mystery. Even the existence of ordinary matter remains a mystery since, so the argument goes, if every time a particle is created an anti-particle is also produced and if every particle and anti-particle has the capacity to annihilate its opposite, all particles and anti-particles ought to have mutually destroyed each other within a few moments of the creation of the Universe.

What, then, is the explanation for the existence of matter without the corresponding anti-matter? Particle physics should be able to provide a comprehensive explanation of why we are able to exist as we do, and this aim in itself is more than adequate justification for continued research.

How far have we got?

The picture of the Universe which has so far emerged from particle physics research is basically a very simple one, as we have seen. However, we still have some way to go before we achieve a comprehensive description of the influences, or "forces" as they are often called, which the particles exert on each other. We are aware of some of these forces in everyday life, such as the electric and magnetic forces and gravity (falling objects). Other forces have such a limited range of influence that we are only indirectly aware of their existence. This is true, for example, of what is termed the "strong" force which binds together the quarks making up the protons and the neutrons (see pages 33 and 34) and similarly holds together the protons and neutrons in the nucleus of the atom (page 35). The same is true of the "weak" force which is partly responsible for the instability of unstable particles (page 11).

The challenge facing modern particle physics research: how to explain the immense variety of objects, structures and other phenomena observable in the Universe by means of a small corpus of laws governing all particles produced from the condensation of energy.

But how do these forces work? How are they transmitted from particle to particle across empty space? The current interpretation is that various types of so-called "messengers" are exchanged between the particles. These short-lived "messengers" cannot really be called particles, still less objects, but you could try and visualize them as "whirlwinds of space". Although this expression has very little meaning, it has at least the merit of reminding us that we have reached a point where things can no longer be expressed in everyday terms.

How far will we get?

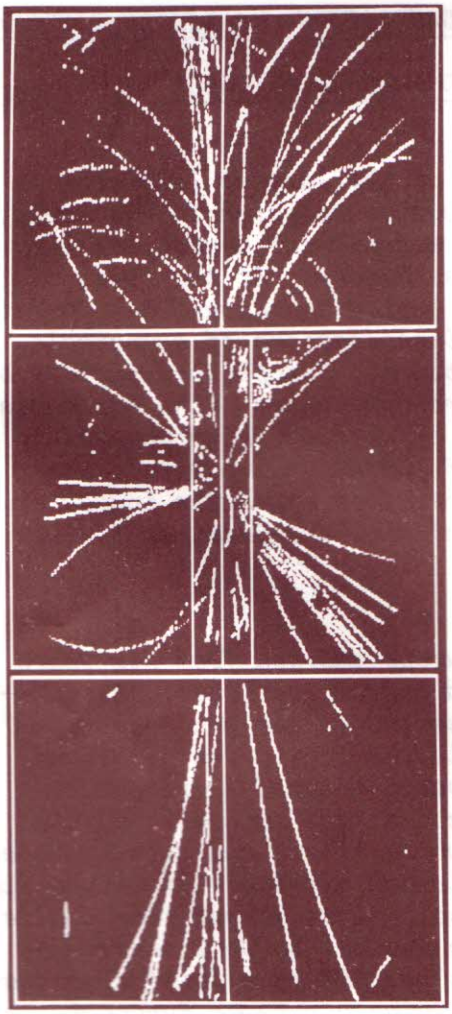
We have seen that the ultimate goal of particle physics is to achieve a clear, coherent and comprehensive description of the Universe in terms of what we have called in this booklet "particles", "points" and "messengers". Discoveries such as that of the "intermediate boson" (see opposite page) increase the hope that this goal can be attained. But will we really ever be totally successful? The physicists are themselves divided on this point.

- There are those who believe that ultimately we will achieve success and that then scientific research will be primarily devoted to the study of complex astronomical, physical or biological phenomena, such as the workings of the brain, for example.

- Others think that, as in the past, there will always be something further to discover in the world of the infinitely minute and the "absolutely fundamental".

- Finally, a minority of physicists holds the view that one day man will be forced to recognize the impossibility of further research owing to the insuperable technical, and possibly even intellectual, problems that it will pose ...

Who is right? Only time will tell. In the meantime, research goes on.



Careful study of tracks such as those illustrated above led to the discovery of a "messenger", the intermediate boson, which had been actively sought for many years.

An example of a recent discovery: the intermediate boson

In 1983, after a ten-year world-wide search, a "messenger", whose existence had been predicted by the theorists, was discovered at CERN. This development has been hailed as a discovery of major importance by all the specialists in the field and has enabled physicists to establish a close connection between two types of apparently different forces: the "weak" and "electromagnetic" forces. This discovery marks another stage in the process begun in the nineteenth century when the magnetic and electric forces were explained and described by the same set of equations, and is a further step forward in the complex search for a single Law which could provide an explanation for all the "forces" and, therefore, possibly even for all the forms that energy can take when it condenses into matter. For this discovery, two CERN researchers, Professor Carlo Rubbia and Dr Simon van der Meer, were awarded the 1984 Nobel Prize for Physics.

To conclude this brief introduction to particle physics, let's take a look at CERN itself.

CERN AS AN ORGANIZATION: A LITTLE HISTORY AND A TOUCH OF PRIDE

CERN, one of the largest laboratories for particle physics research in the world, is situated at Meyrin near Geneva astride the Franco-Swiss border. At the present time, only the United States and the Soviet Union possess installations of comparable size and importance. Established in 1954 by twelve West European states, CERN harnesses the collective efforts of their physicists in the field of fundamental particle research - a cooperation which was indeed one of the principal aims the Organization set out to achieve (*).

In 1945 Europe emerged from six years of war weakened and impoverished. As individual countries lacked the financial resources to build the costly installations required for modern scientific research, many European scientists emigrated to the United States where modern and well-equipped laboratories already existed. It was to stem this drain of scientists abroad that twelve European states decided to pool their resources and set up CERN as a joint organization, thereby giving a renewed European impetus to what was then termed, by approximation, "nuclear physics".

More specifically, the purpose of the Organization was to provide opportunities for particle physics research, i.e. the study of the fundamental structures of matter, a subject which has only incidental associations with nuclear fission (i.e. the production of energy from the nuclei of certain atoms such as those of uranium). Moreover, the Convention for the establishment of CERN defines very strictly the aims and objectives of the Laboratory and expressly prohibits any research for military purposes. Nor should CERN be confused with a nuclear power station. The Laboratory's sole aim is to study the transformation of energy into matter and all the phenomena which are revealed by this transformation, such as the structure of matter at the level of the infinitely small and the most fundamental forces at work in Nature.

(*) There are fourteen Member States in 1986; they are : Austria, Belgium, Denmark, France, Germany (Federal Republic), Greece, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom.

Since its inauguration in 1954, CERN has made it possible for physicists, little by little, to restore European excellence in the field of research to its pre-War level, enabling the Old World to make up ground lost to the New. The setting-up of CERN also marked the restoration of a very long European tradition of scientific and intellectual exchange and from its beginnings, the Organization has contributed to the re-establishment of fruitful and friendly contacts between countries formerly divided by war.

Today, CERN acts as host to more than 3000 research physicists from Europe and from many other countries throughout the world. Large numbers of experiments are conducted by teams of scientists which are international in composition and involve the active participation of many national institutes.

The results of the research work undertaken are difficult to describe in everyday terms, but it is well known that many major discoveries have been made at CERN over the last twenty years, a success story which is due in no small part to the sophisticated machines CERN possesses and to the exceptionally high calibre of its engineers. The latest result of this marriage of science and technology has been the production, storage and acceleration of anti-protons for experiments of a new kind: collisions between "matter and anti-matter".

The scientific cooperation cultivated by CERN is in its way something of a miracle: certainly no other international laboratory operates on this scale. It is not only that the scientists working there come from all parts of the world: the machines themselves are the product of the combined efforts of European industries specializing in the very latest techniques. Thus, it is not unusual to find an instrument with a precision of a few thousandths of a millimetre, comprising components manufactured in a variety of different countries and yet doing its job to perfection.

CERN has an "open-house" policy, in the sense that all the results of its experiments are published and generally available for physicists from all over the world to consult. Similarly, the technological innovations developed at CERN for the construction of one or other of its machines are regarded as public property: CERN does not patent its techniques and anyone is free to make use of them.

The Member States govern CERN through the intermediary of a Council which meets twice a year. A Committee composed of European and non-European physicists meets regularly to discuss present and future research programmes and makes recommendations to the Council. An efficient administration puts into effect the policies decided by the Council, with the handling of the Organization's financial affairs under the supervision of a Finance Committee. CERN's current annual budget is about 755 million Swiss francs, which represents three Swiss francs a year for every man, woman and child in the Member States.

Thus, for what is, after all, a modest sum CERN successfully maintains its position at the forefront of world particle physics research. Over and above the results it achieves in this field, the research itself and the concentration of talent at CERN are of inestimable value for the cultural development of Europe.

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