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"Scienza: certezze e stupore. La testimonianza di uno scienziato"

a cura di
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1 Introduction

My subject tonight is *the nothing*. Unfortunately, it takes much longer to *speak* of the nothing than to *say* nothing. To simplify the task, I shall use the technique employed by any tourist organisation which has to guide newcomers in the tour of the many historical sites of a foreign town. *First*, I shall choose only some of them, either the most ancient ones or the most unusual ones, leaving aside the pretension of being complete. *Second*, I shall shortly describe the *three* chosen sites even before starting to move, so that each one of you will know in advance what to expect. *Lastly*, I shall use many images to make the subject as concrete as possible.

The overall theme of the visit is *the nothing*, that is what remains when everything which can be removed from a certain region of space is removed. To be more specific, let us consider a 1 m^3 volume far away in the interstellar space. Such a volume has *three* dimensions (height, depth and width) because we live in a threedimensional world. At the start this volume will contain some interstellar powder, molecules, and atoms and will be traversed by cosmic rays, light and electromagnetic waves coming from all directions. Let us suppose that, after isolating it completely from the surroundings with thick walls, we have powerful enough pumps to remove from it *all* what is there. Common sense would tell that, after such an operation, inside *nothing* is left.

But what *is* nothing? The history of Western philosophy has been marked by this question, sometimes put in the more philosophical form: what is the *non-being*? About 450 years B.C., *Parmenides* said '*non-being is not*' and '*one can neither know the non-being ... nor demonstrate it*'. About fifty years later *Democritos* took the opposite stand: '*Being exist by nothing more than non-being*'. He concretised the difference by conceiving being as *plenum* (or fullness), represented in his view by indivisible atoms, and non-being as *vacuum* (or emptiness). According to Democritos the non-being is the empty space in which the atoms move and it is equally constitutive of reality as the atoms themselves.

Ontology, which is the discourse on 'being' and 'non-being', has been a fundamental one in Western philosophy. Many would say that on this subject every possible point of view and also its opposite have been defended along the centuries. They would contend that it makes no sense to compare the views that modern physicists have on the vacuum with what was conceived by the phantasie of ancient thinkers with no scientific background. On the contrary, I think that the comparison is useful, for at least two reasons. *Primo*, by connecting our views with the history of ideas it comes into light the fact that many of the problems addressed today by scientists have their roots in the questions put long ago by philosophers. And this enlightens the unity and generality of human thinking. *Secundo*, today physical conceptions of the nothing are very rich, in fact richer than the one imagined by any philosophical system, and they can, and should inspire modern thinkers who are still interested in ontology. As we shall see, a divorce between physics and ontology took place in medieval times, a divorce which should have been repaired long ago.

2 Two warnings

But before introducing you to the three sites to be visited, I have to express two warnings. I am an experimental physicist, not a professional philosopher, so I shall not engage in profound discussions of philosophical problems. I shall simply try to put into light some interesting analogies. Moreover, when speaking as a physicist, I shall take the point of view of *naive realism*. It is well known, even to non-philosophers, that nothing can be claimed with certainty of the physical world 'out there'; at best we should always say 'things appear to us as if there was such a particle, endowed with energy, which moves through space, which does this and that ...'. I shall speak instead of a particle with energy as if we could be sure that it is *really there* to produce the effects we observe. And the same applies to the fields I shall introduce. This is simple and practical and, after all, corresponds to what most physicists assume while working in the laboratory. But the same scientists are ready to criticise it in learned discussions because naive realism contradicts some subatomic physics experiments and on logical ground is unfounded. Still, for simplicity's-sake I take the risk.

3 Overview of the visit

At the end of the visit the conclusions will be: 'The physical vacuum is *not* the absolute nothing; however, our present understanding is reminiscent of some ancient metaphysical views of the non-being. And indeed it is much richer and more varied than what the philosophers of the past imagined.' This conclusion will be reached by guiding you through three items, which can be identified as:

(i) the classical vacuum;

(ii) the melting of the new vacuum;

(iii) the fluctuating vacuum.

Let us shortly go through each of them in turn.

(i) According to the physics of the beginning of the century, the so called *'classical'* physics studied in high schools, matter is made of small bodies called *'particles'* while light, and all radiations, are *'waves'*. By removing *all* particles and *all* electromagnetic waves from the box which we left suspended there, in the interstellar space, a physicist of the 1920's would have concluded: inside *nothing* is left. This 'classical' view of the vacuum is similar to the very first one proposed by Democritos 400 years B.C.. [Thus only seventy years ago a physicist, giving a talk on 'the physical vacuum and the metaphysical nothing', after some remarks (which I shall address later) would have concluded 'the physical vacuum *is* the non-being'. This is the first, by now ancient and superseded, site we shall visit.] Its name is *'the classical vacuum'*.

(ii) Indeed by penetrating the world of the atoms, our recent predecessors have been obliged to change opinion. After a lot of struggling with incomprehensible data, at the beginning of the 1930's a *new physics* was born. [Only through it the phenomena taking place in atoms and nuclei and the creation and destruction of matter-particles and matter-antiparticles could eventually be understood. The new physics has many names; the preferred one is *'quantum field theory'*. By using this theory, the inner working of lasers, the variety of chemical compounds, the existence of antiparticles and the like can be explained. To achieve all these successes physicists had to drastically modify their view of the microscopic world.] Particles lost their role of fundamental entities in nature. *New* entities extended to the whole of space had to be introduced: *the fields*. In preparation for the visit to the second site I shall illustrate this fundamental change of perspective both on matter and on vacuum. And then, armed with these new concepts, we will be ready to describe what happens in the annihilation of matter and antimatter which we do daily at LEP, the 27 km collider which is placed 100 meters under ground near Geneva. At LEP we observe the *'melting of the new vacuum'*, the name of the second site to be visited. This vacuum is different from the one of the Greek atomists, but has something in common with the neoplatonic views. A presentation of these philosophical ideas will conclude the visit to the second site.

(iii) Because of the presence of the fields, the vacuum is *not* the state of absolute nothingness. But this is not the whole story: the fields are not static. On the contrary, they continuously pulsate, even in the absence of any external perturbation. For this reason the vacuum is a dynamic entity, it is in a state of permanent change, it continuously quivers in a way which can be detected by our instruments. This is the reason for the title given to the last site we shall visit: '*the fluctuating vacuum*'.

Figure 1 lists once more the themes we shall elaborate on:

1. classical vacuum
2. melting of the new vacuum
3. fluctuating vacuum.

Let us now get on board the busses waiting for us and start the tour.

4 The classical vacuum

In the one m^3 box, before trying to empty it, there are molecules and atoms. Before removing them we better know what they are from the point of view of a "classical" physicist. Molecules are made of atoms, which, in turn, are made of matter-particles. **Figure 2** shows the inner structure of an atom. According to *classical physics* matter-particles are microscopic balls which attract each other: negative electrons rotate around the positive nucleus as satellites around the sun. More recently it has been discovered that neutrons and protons are made of two different types of '*quarks*' bound three by three; electrons and quarks are the smallest bits of matter, so small that nobody has yet succeeded in measuring their diameter.

Let us now suppose that all these matter-particles have been pumped out from the box. Have we obtained the absolute vacuum? Unfortunately not, because inside the box there are still electromagnetic waves which propagate from one point to the next, moving with the speed of light. These waves, as anticipated, are perturbation of the electric and magnetic fields. The ones which come from outside the box in form of light, radio-waves and X-rays can be shielded with thicker and thicker walls. But this is not enough, because the walls themselves continuously emit (and absorb) electromagnetic waves. This is well known in the case of a piece of metal which is heated up to about 1000 degrees. The metal becomes red because it radiates electromagnetic waves as a consequence of the continuous agitation of its electrons and its atoms. This radiation is there, but much less intense, also when the metal is at ambient temperature. Thus, at *any temperature* the inside of the box is always full of electromagnetic waves continuously emitted and reabsorbed by the walls and there is *no way* to pump them out!

To eliminate them we have to reduce the temperature of the walls to the minimum possible temperature, the *absolute zero*. This temperature is 273

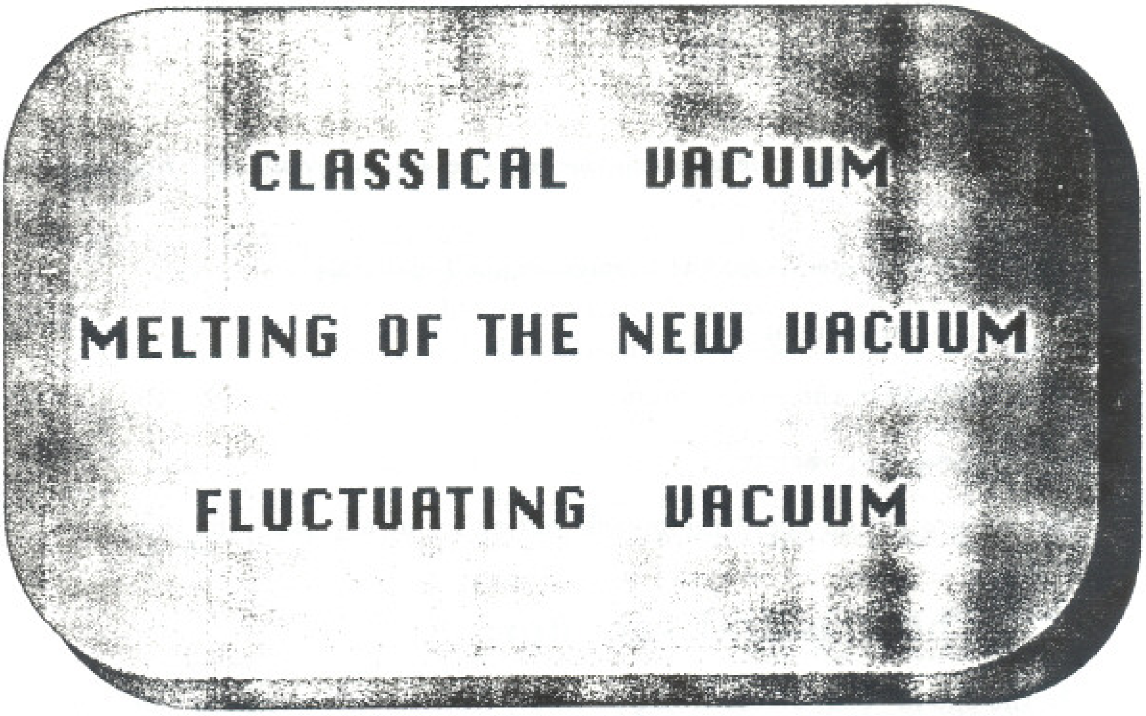


Fig.1 Classical vacuum, melting vacuum, fluctuating vacuum

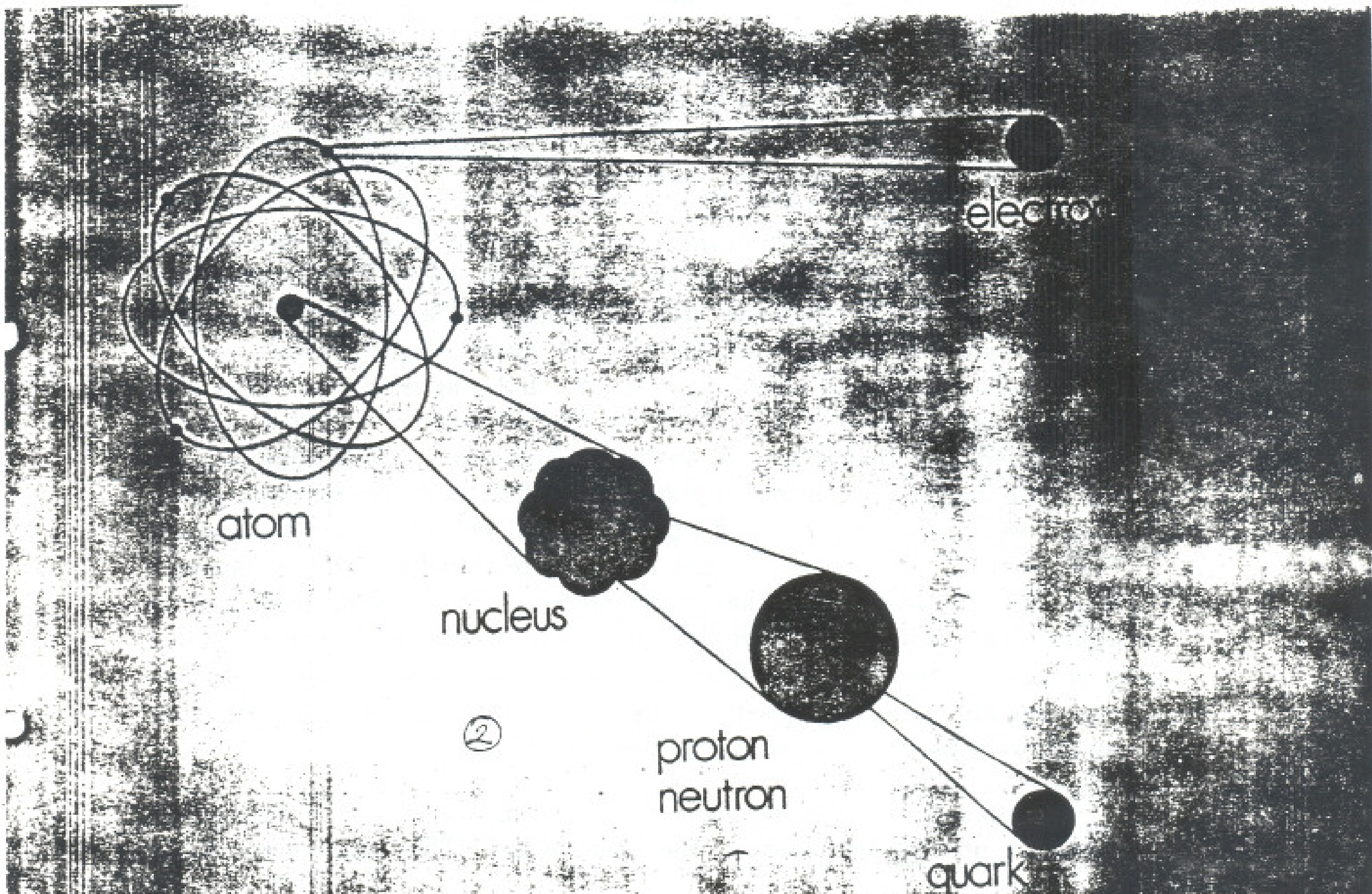


Fig.2 Atoms, nucleus, protons, neutrons and quarks

Fig.3 De Rerum Natura: some verses

Fig.4 Einstein

degrees Celsius below the freezing point of ice. At such a low temperature, *according to classical physics*, matter-particles stop agitating and thus do not radiate electromagnetic waves any longer. In an empty and cooled box there is no matter, no radiation: we have eventually produced a vacuum which is the *absolute nothingness*.

In conclusion, according to the classical description, the vacuum conceived as non-being by Democritos, Epicurus and other atomistic philosophers, *can* be produced: it needs the removal of *all* matter-particles and the cooling of the walls of the box to -273° Celsius. Because of this, the point of view of Democritos with regard to the nothing was considered to be still valid by the scientists of sixty or seventy years ago.

Two thousand years before a latin writer, *Lucretius*, described poetically in "De Rerum Natura" the point of view of the atomists. To end the first visit let us read together some verses of this long poem, which are reproduced in **Figure 3**.

> 'One should not believe that matter is everywhere ... because there is an impalpable and empty vacuum. If it was not, things could not move: indeed their typical property of opposing and resisting would never allow any movement. Nothing could go forward since nothing would start to let. We see many things which move in different ways in the seas, on earth and in the heights of the sky. But, if vacuum did not exist, not only the bodies would lack any agitation, but they would not have being generated at all, since matter, compressed from all sides, would have remained at rest for ever.'

5 Mass and antiparticles

The trip to the second site is much longer because I have to justify why this classical view of vacuum is untenable today. Its crisis has many roots; the simplest to grasp is the discovery, made in the 1930's, that matter-particles are not eternal, but can disappear by transforming into energy.

There are *two* steps in the argument. The *first* one is based on the *mass-energy equivalence*, which made Albert Einstein world-famous. **Figure 4** shows Einstein around 1905, when he made his revolutionary proposal. The equivalence principle states that mass can be converted into energy and, vice-versa, energy into mass. Since then we know that the mass of each matter-particle can be thought simply as *frozen energy* (**Figure 5**). This energy was endowed to the particle once and for all to make it real and it cannot be dissipated. Having this minimum energy the particle stays put for ever and this is the reason for which in the figure it is written that the mass, when the particle is *at rest*, is frozen energy. If further 'kinetic' energy is added, the mass increases and the particle moves faster and faster. This phenomenon happens in all *particle accelerators*. For instance, an electron accelerator is an instrument which increases the mass of the circulating electrons; by getting a small amount of extra energy at every turn they acquire mass and increase their velocity until they get very close to the velocity of light. This velocity is the *limiting speed* for all bodies and cannot be bypassed whatever energy is given to the accelerated particle. To be consistent with this description, particle accelerators should be rather called *massificators*: as indeed the velocity practically does not increase [once the particle has reached the velocity of light] while its mass continues to increase.

Accelerators or massificators, these are the main instruments we have at our disposal to explore the subatomic world. **Figure 6** is a photograph of the main accelerators installed at CERN. Electrons are accelerated by PS and the SPS, the smallest circles, and then injected in LEP, the Large Electron Positron Collider which is the largest circle in the photo. LEP is the largest science instrument ever built on Earth; it is the place where the vacuum is heated at the highest temperature, as we shall shortly discuss. **Figure 7** shows the tunnel of LEP 100 meters under ground, with its magnets, which bend the particles and keep them inside the 27 km long circular evacuated beam pipe which is shaped as a doughnut. The 'cavities' of **Figure 8** contain an alternating electric field, which gives a kick to the particles at every passage; inside them the energy of the electric field transforms into mass of the circulating electrons. All these instruments work on the basis of the equivalence principle: in LEP, for instance, the mass of a circulating electron is *hundred thousands times* larger than the minimum energy an electron can have, which is the energy frozen in its mass when the electron is standing still before being accelerated. The fact that LEP works is the best demonstration of the first step in the argument we are building up.

The *second* step of the argument has to do with *antiparticles*. In the 1930's it was found that by spending energy one can create from scratch new matter-particles which carry the same mass of an electron, but a *positive* (instead then a negative) *electric charge*. This new particle, called '*positron*', is endowed with the *same* frozen-energy as an electron, but has *opposite* charge.

A positron is called the 'antiparticle' of an electron; quarks also have their own antiparticles: the antiquarks. The pair creation of a particle and antiparticle is an enormous extension of the possibilities previously available

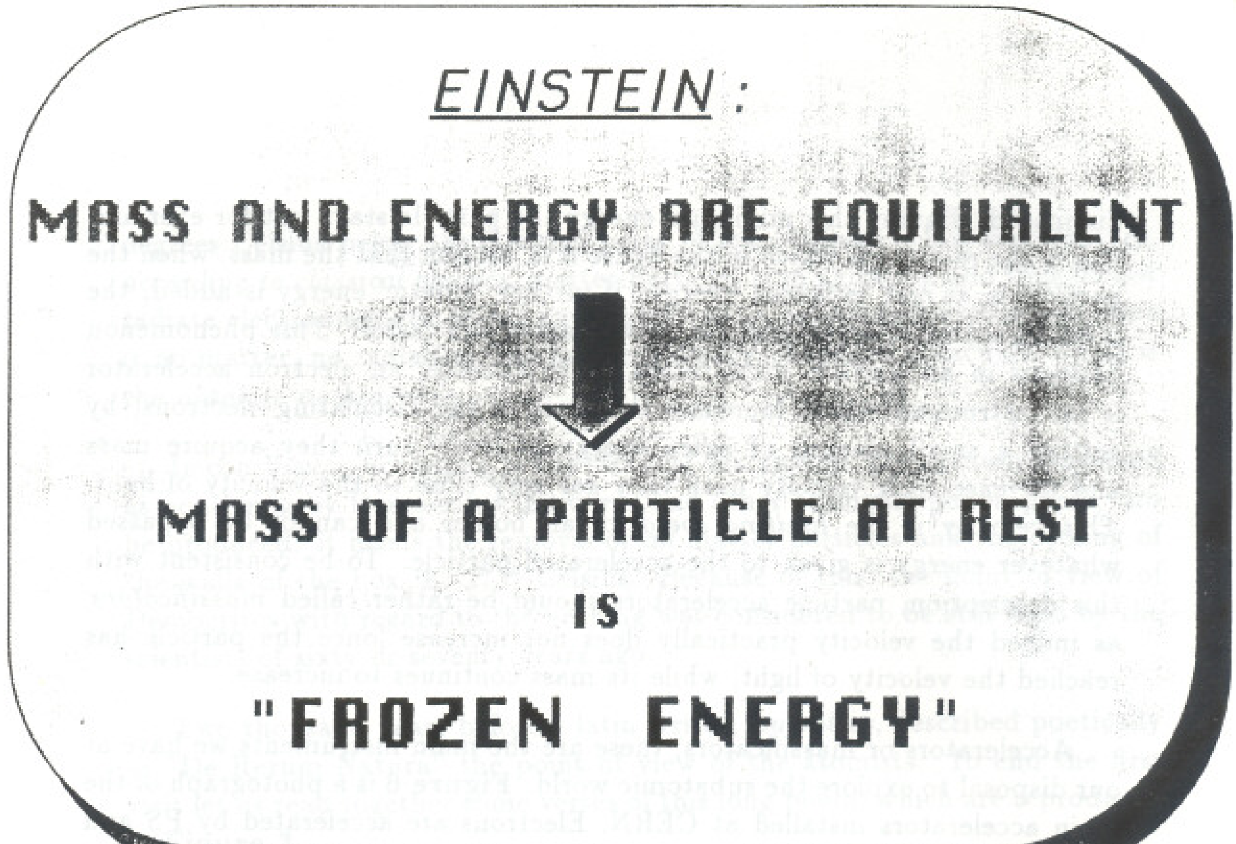


Fig.5 Mass = frozen energy

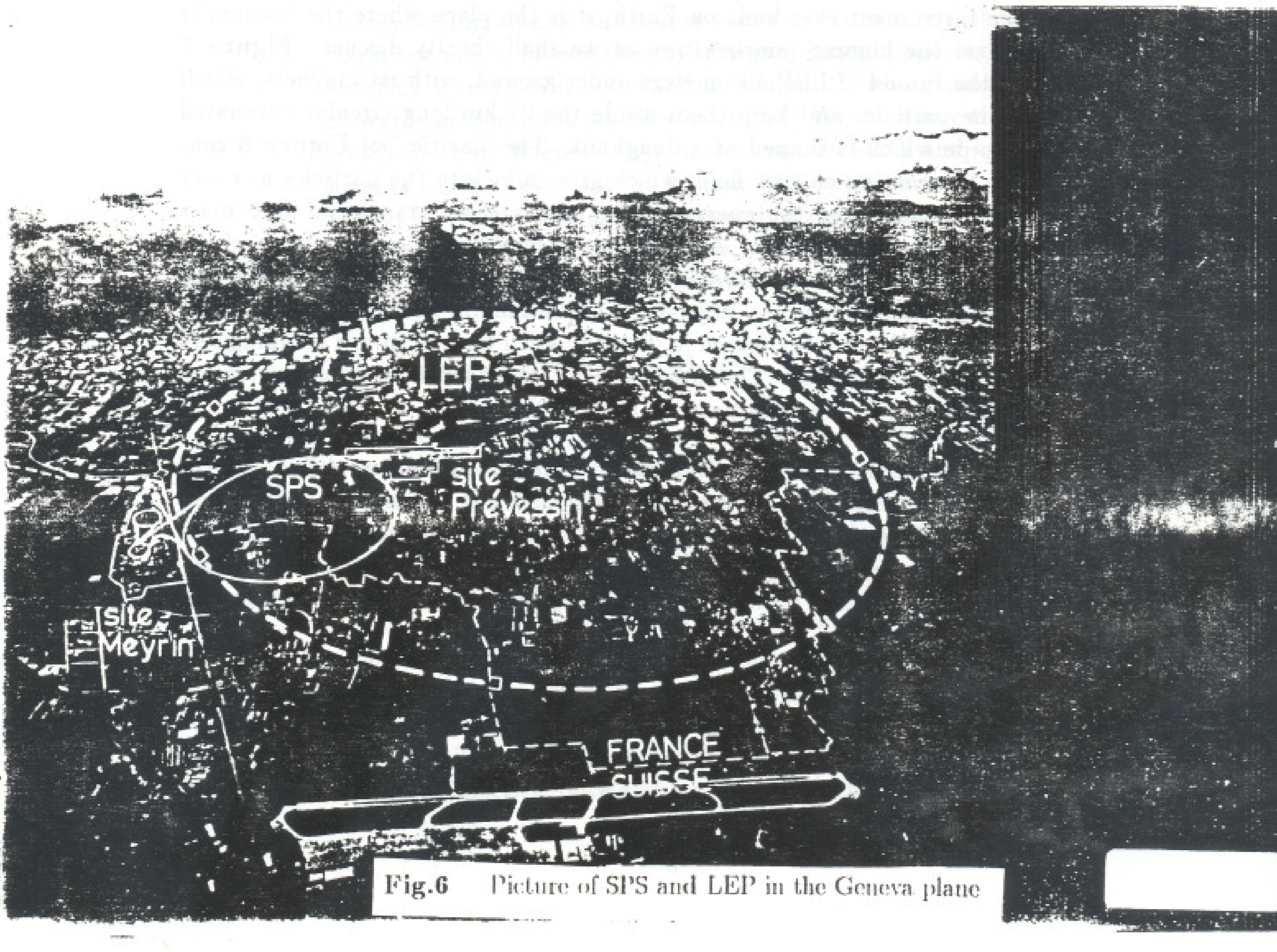


Fig.6 Picture of SPS and LEP in the Geneva plane

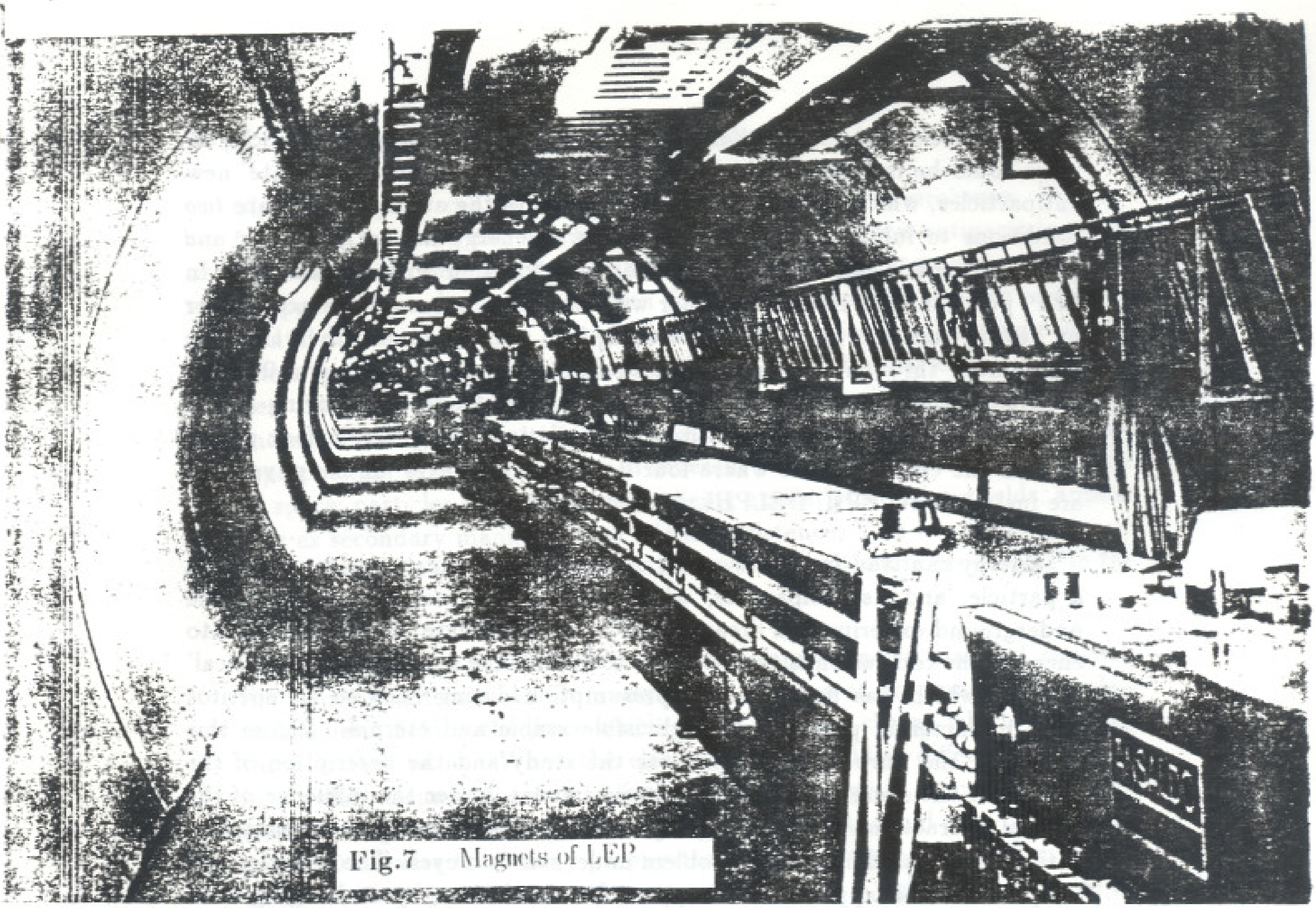


Fig.7 Magnets of LEP

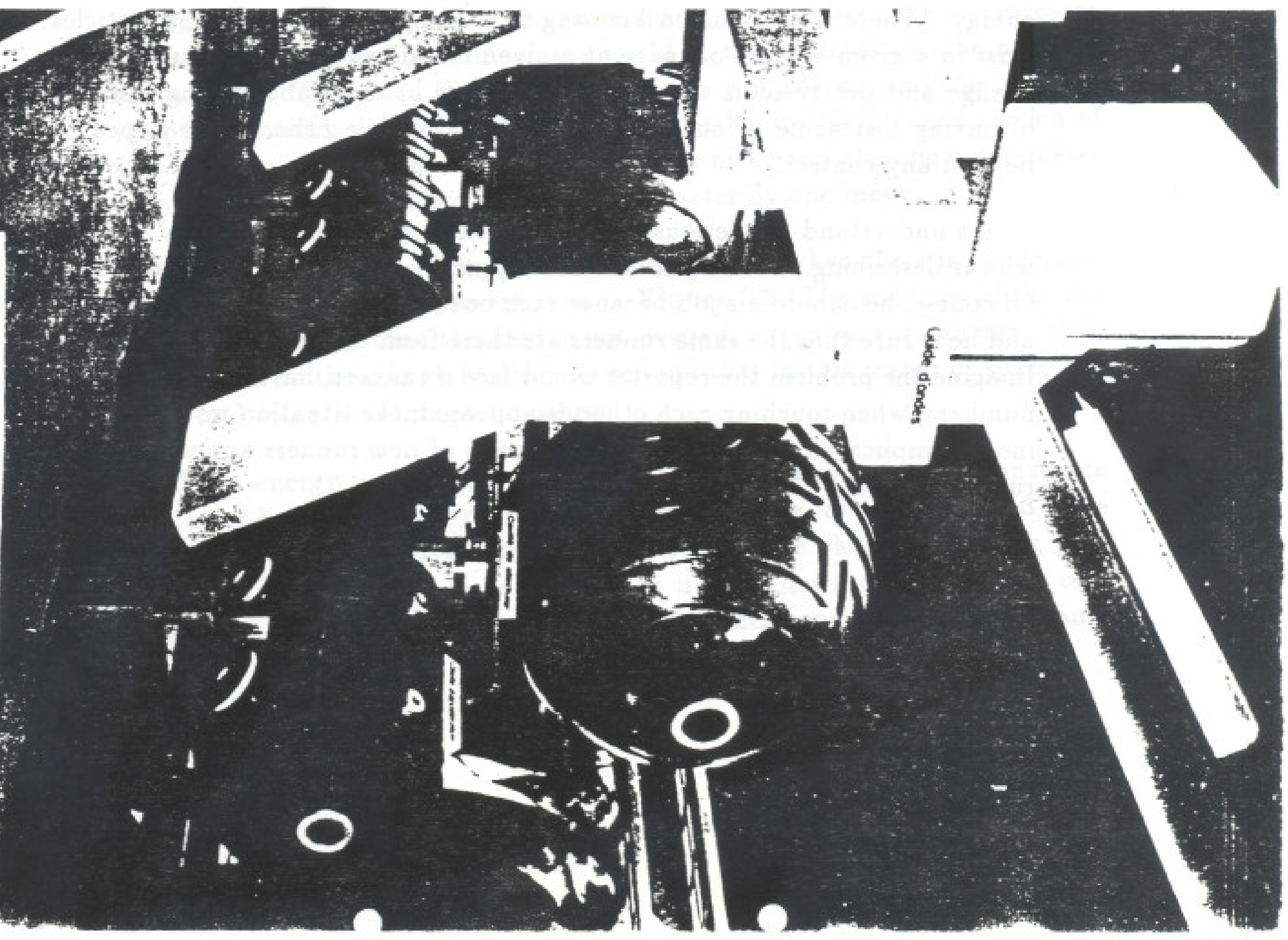


Fig.8 Cavities of LEP

to us. Einstein had taught that, by giving energy to an existing particle, its mass could be increased; but, by spending energy, we can also 'create' new antiparticles, which are not stable components of the atoms. [There are *two* conditions to fulfill: an equivalent amount of energy has to disappear *and* each antiparticle has to be always produced together with its particle.] In LEP, positrons are created together with electrons in a separate accelerator by having high energy electrons crashing into a metal target; then they are accelerated through the same PS and SPS accelerators (**Figure 9**), and eventually they are stored in LEP as are the electrons, but moving in the opposite direction. Electron-positron annihilation take place in four points around the circumference where four detectors, the 'eyes' of the physicists, are installed: ALEPH, DELPHI, L3 and OPAL.

Energy can transform into a pair of particles and antiparticles; vice-versa a particle, and its antiparticle, when meeting (for instance in one of the underground experimental areas of LEP) can 'annihilate' and transform into energy. The conclusion is that we have to modify the description of 'classical' physics, which was based on the presumption dating back to Democritos that fundamental particles are indivisible stable and eternal. Before this discovery, the purpose of physics was the study and the description of the motion of the same unchanging matter-particles, under the influence of the mutual interactions. Mass-energy equivalence *combined* with the existence of antiparticles has changed the problem under our own eyes. The particles and antiparticles can appear and disappear here and there by exchanging their existence with the disappearing and appearing of a corresponding amount of energy. [There is no point in knowing how many particles and antiparticles exist in a given volume of space at a given instant of time; this number will change and pretty soon we will find ourselves in the embarrassing position of having lost some of our observable objects, while others have appeared beyond any control.]

To understand the seriousness of the situation, let us consider a reporter who is describing at the radio the development of a marathon (**Figure 10**). Of course, he can do his job because each one of the runners wears a number and he is sure that the same runners are there from the beginning to the end. Imagine the problem the reporter would face if runners, having even and odd numbers, when touching each other disappeared; the situation would be even more complicated if from time to time pairs of *new* runners appeared in the running crowd.

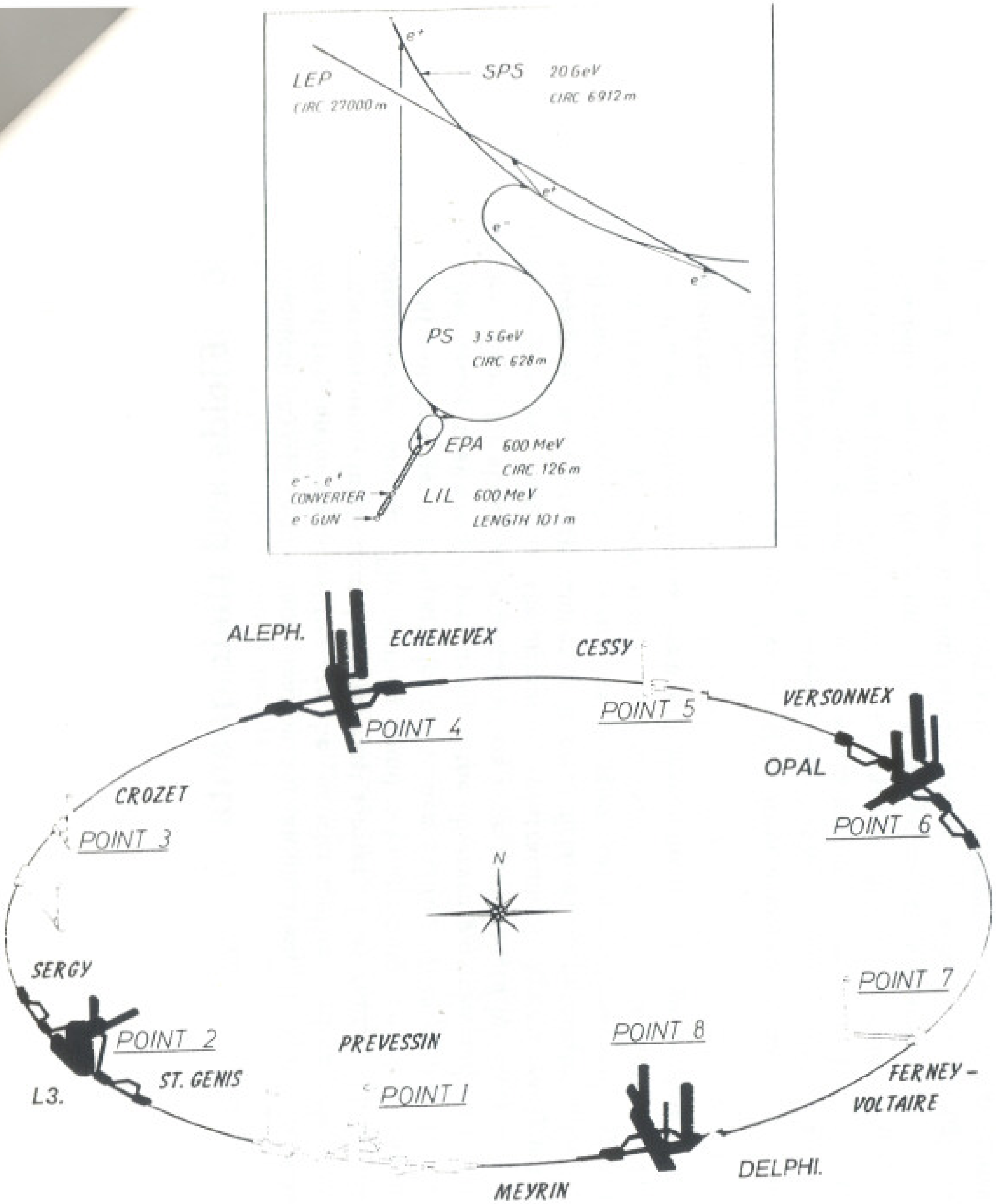


Fig.9 Design of the accelerator complex at CERN

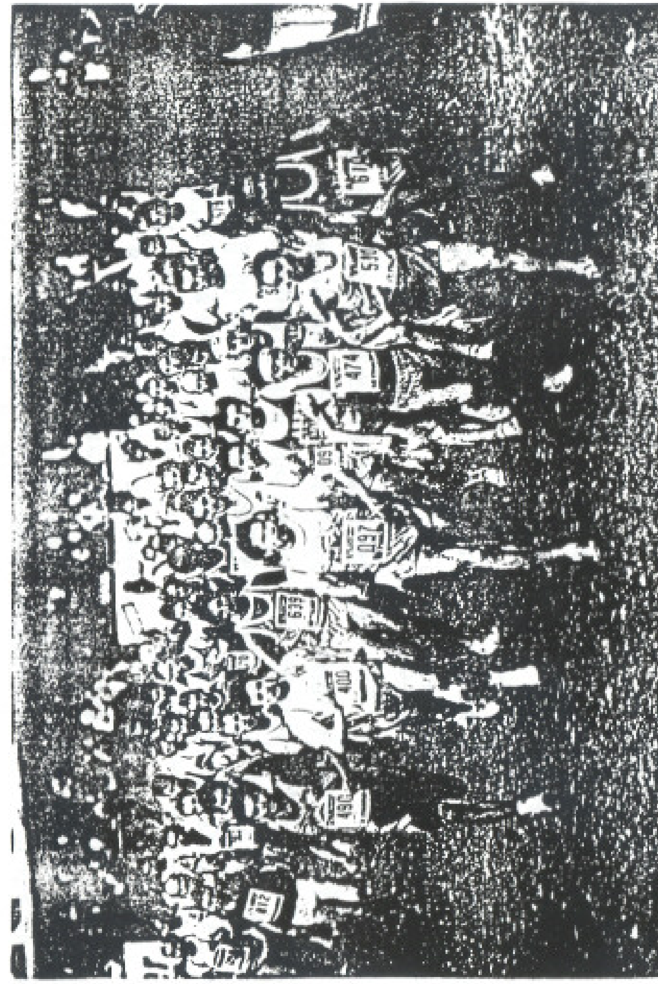


Fig.10 Photo of a marathon

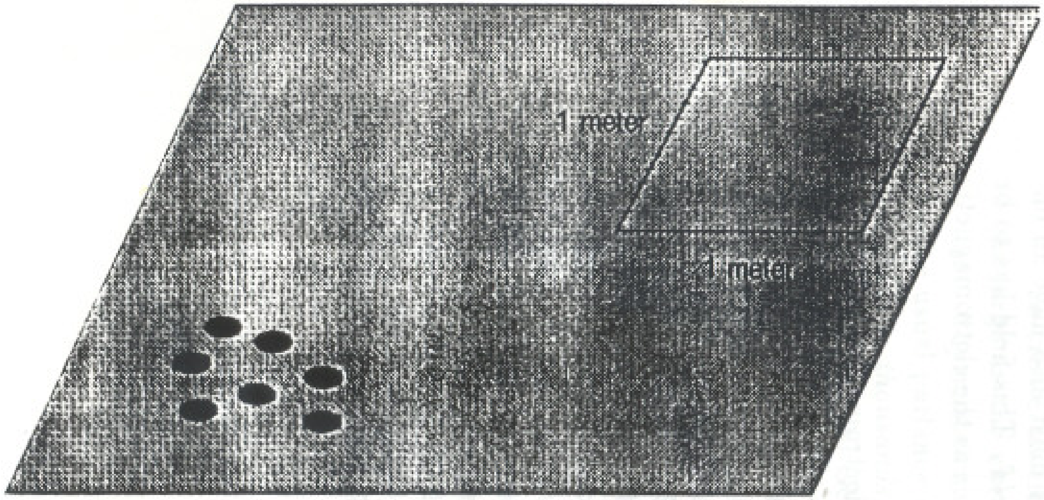


Fig. 11 Flatland

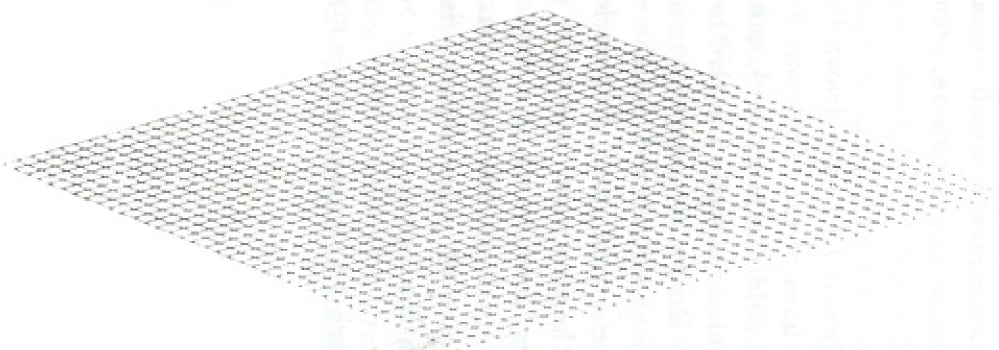


Fig. 12 Region of space with no electromagnetic field

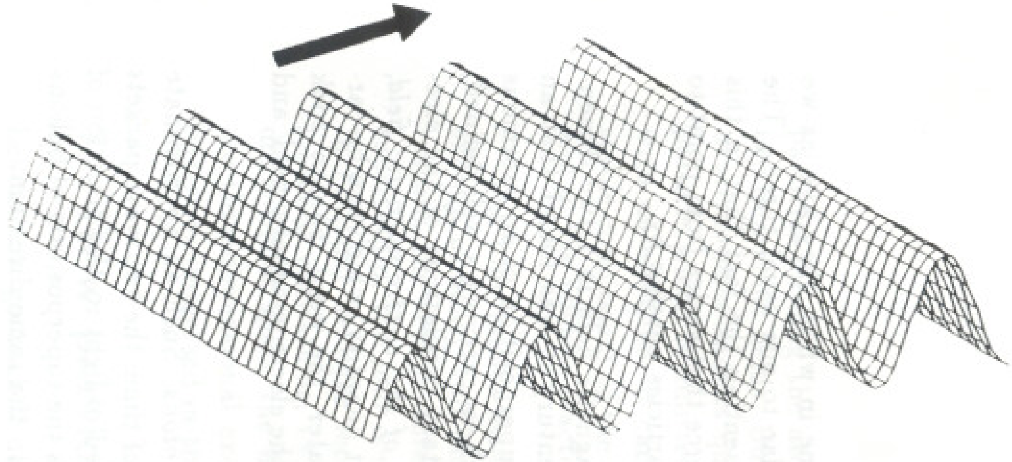


Fig. 13 Classical electromagnetic wave

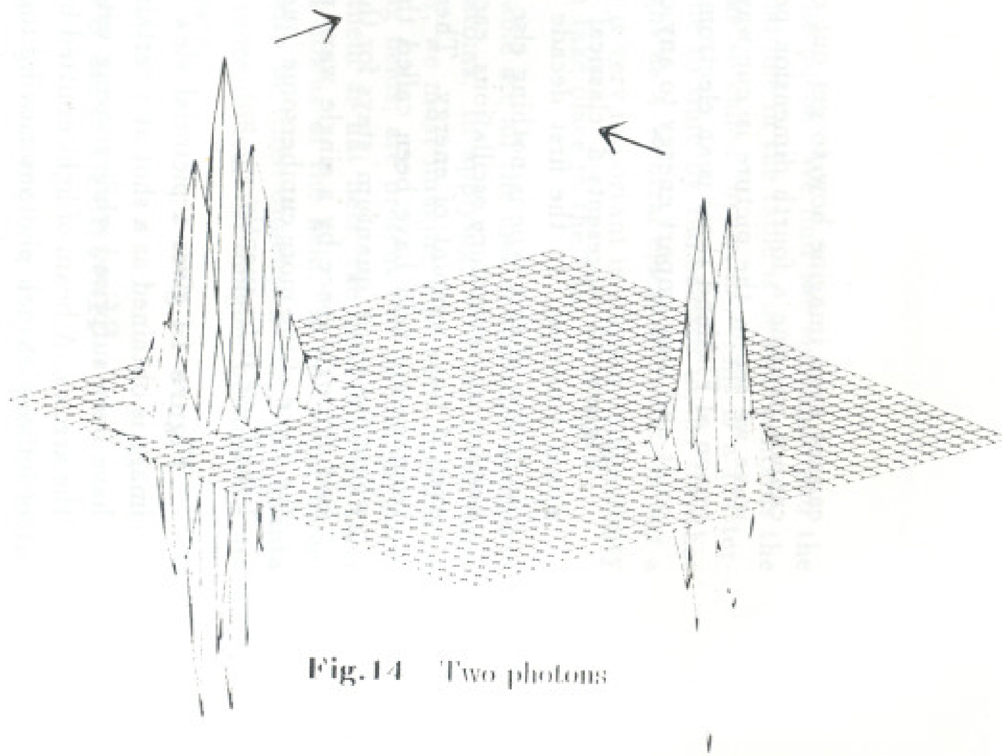


Fig. 14 Two photons

6 Fields and their quanta

Classical physics cannot face creation and annihilation processes, because for it the *fundamental entities* are the particles and the antiparticles and, by assumption, fundamental entities exist forever. They cannot appear and disappear at random. The solution found is to attribute the role of fundamental objects *not* to the particles but to *new entities which extend over the whole space*; they are the precursors of the observed particles and antiparticles. Thus, for about 50 years physicists have been *obliged* by experimental findings to recognise that the primordial substratum of physical reality is the superposition of a large number of different *fields* which permeate uniformly all space; particles and antiparticles, being excitations of these fields, appear only as secondary manifestations of their existence. This is a subtle concept and it is worthwhile slowing down and developing it before proceeding to the second site.

What really is a field? Let me start from a known classical concept: the electromagnetic field. In every point of space at any moment the electromagnetic field is the *force* which would act on a charge which is passing through that point. When the electromagnetic field is different from zero in a point, around that point electromagnetic energy is concentrated. This energy can get transferred to an electric charge that would pass through the point. Otherwise the energy propagates to the nearby points, and gives rise to an *electromagnetic wave*. How can we represent a field? In our three dimensional space it is very difficult, because the field extends over the three dimensions and we live inside the same space in which we have to represent it. It is much easier if we imagine a world in two dimensions; the name of this world is *'Flatland'*. **Figure 11** represents you and me and the 'volume' in space of which we are talking so much tonight; in this reduced version of the Universe we are represented as small flat disks and the one cubic meter volume is a *surface* having an area of one meter by one meter.

Let us take a very small portion of this surface: when there is no electromagnetic field we can represent it as in **Figure 12**. The red lines of the net are *flat* to indicate that the field is not excited, it contains *no* energy. Still, the net can be thought to be there to remind that in this region of space one *could* find some elctromagnetic energy.

When energy is there and an oscillation propagates, caused for instance by a laser beam, a proper representation may be the one of **Figure 13**. The oscillation extends over a region of space. But one should not think that there is a kind of *water-wave* which goes up and down on the surface of a lake while moving. Flatland has only two dimensions; its flat inhabitants cannot even imagine how to get out of the plane in which they live [as we cannot imagine a fourth dimension perpendicular to our usual three.] The wave we see in the picture is *our* way of representing the fact that in this region of Flatland there is an electromagnetic force that varies from point to point and may impart energy to any charged particles passing by.

Figure 13 represents a 'classical' electromagnetic field in a two dimensional Universe. In the first decade of this century it was found that an oscillation of this type is nothing else but the superposition of an enormous number of *elementary* oscillations, each one of them carrying a well defined, even if tiny, amount of energy. These elementary oscillations of the electromagnetic field have been called the *quanta of the electromagnetic field*, where the word 'quantum' stays for the 'smallest quantity' which can be carried through space by a single wave packet. Later, the word *'photon'* took the place of the more cumbersome 'quantum of the electromagnetic field' and I shall use it frequently.

Figure 14 gives a pictorial view of *two photons*. Such an approximate image is obtained as a shot at a certain instant of time; the two wave packets have been surprised while moving with the speed of light in the direction of the arrows. A beam of light emitted by a laser is the superposition of billions of billions of such photons moving together all in the same direction.

Photons are the quanta of the electromagnetic field. In the picture in which *all* particles are the quanta of a field, electrons must also have an immaterial substratum, which we call the *'electronic field'*. This field has to be thought as being everywhere, occupying the same space as the elctromagnetic field.

In **Figure 15** I have drawn the red lines of the electromagnetic field and the blue lines of the 'electronic field' in its quiescent state. The electromagnetic red field can be excited, and indeed in the lower part of the figure there are two photons while the electron field is in its unperturbed state. The description has to be generalised: in the same region of space all fundamental fields are superimposed; for the moment we know the *electromagnetic field*, and the *electronic field*. But nuclei are made of quarks, which are as elementary as the electrons. Two types (called in the physicists jargon one '*up*' and the other '*down*') are the main components of the protons and the neutrons of every nucleus. One must conclude that the vacuum is inhabited also by a *u-quark field* and a *d-quark field*, whose net for simplicity's-sake are not drawn in the figure.

Figure 16 summarises the matter-fields which are needed to describe the particles forming the atoms and the nuclei. We find the electronic and the two quarkonic fields. But the second line in the table is new: it contains the *neutrino-field* and its quantum, the so called '*neutrino*'. This is a matter-particle which is emitted from time to time by radioactive nuclei together with an electron. It can be thought as a 'neutral electron', which is *not* a stable component of the atom, but is very important in nuclear radioactivity and in the nuclear reactions which take place in the Sun.

The *four* quanta listed in the table are all the matter-particles needed to explain ordinary and radioactive atoms. In applying, with the usual *naive realism*, the field picture of matter, we must imagine that their impalpable substratum, the *four* corresponding fields, are present everywhere in space. In Flatland we have represented them as flat nets, the quanta being their localised excitations, i.e. ups and downs of the field. In our usual three-dimensional space the fields are also in three dimensions and the quanta are threedimensional excitations, more difficult to imagine because we are ourselves immersed in the same space.

7 How particle-pairs are created?

Let us now go back to the problem of describing how energy can transform into mass and an electron-positron pair can be produced from energy alone.

To create an electron-positron pair one has to spend an energy at least as large as the energy frozen in the mass of an electron and a positron at rest. Physicists call it *millionelectronvolt* (in short *MeV*). '*High energies*' in the usual parlance of science, are energies much larger than 1 MeV; 1 GeV, which is *thousands MeV*, is already 'high energy'. At LEP energies are of the order of 100 GeV.

Figure 17 describes such a 'creation' phenomenon in Flatland, once fields are assumed to be the primary entities of Flatland. An elementary excitation of the electromagnetic field, having an energy larger than 1 MeV, disappears by producing a 'hill' and a 'hole' in the electronic field. The *hill* and the *hole* are the quanta of the electronic field corresponding to the negative *electron* and to the positive *positron*. In them a fraction of the energy is frozen in the form of mass. The rest of the energy appears as kinetic energies of the two '*quanta of the electronic field*', as indicated by the arrows. Of course the two newly created particles move and separate with time. These quanta of the electronic field are the particles and the antiparticles we observe; but in this new description they are *not* fundamental entities since they are nothing else than wave packets of an impalpable substratum, the field itself. Note that

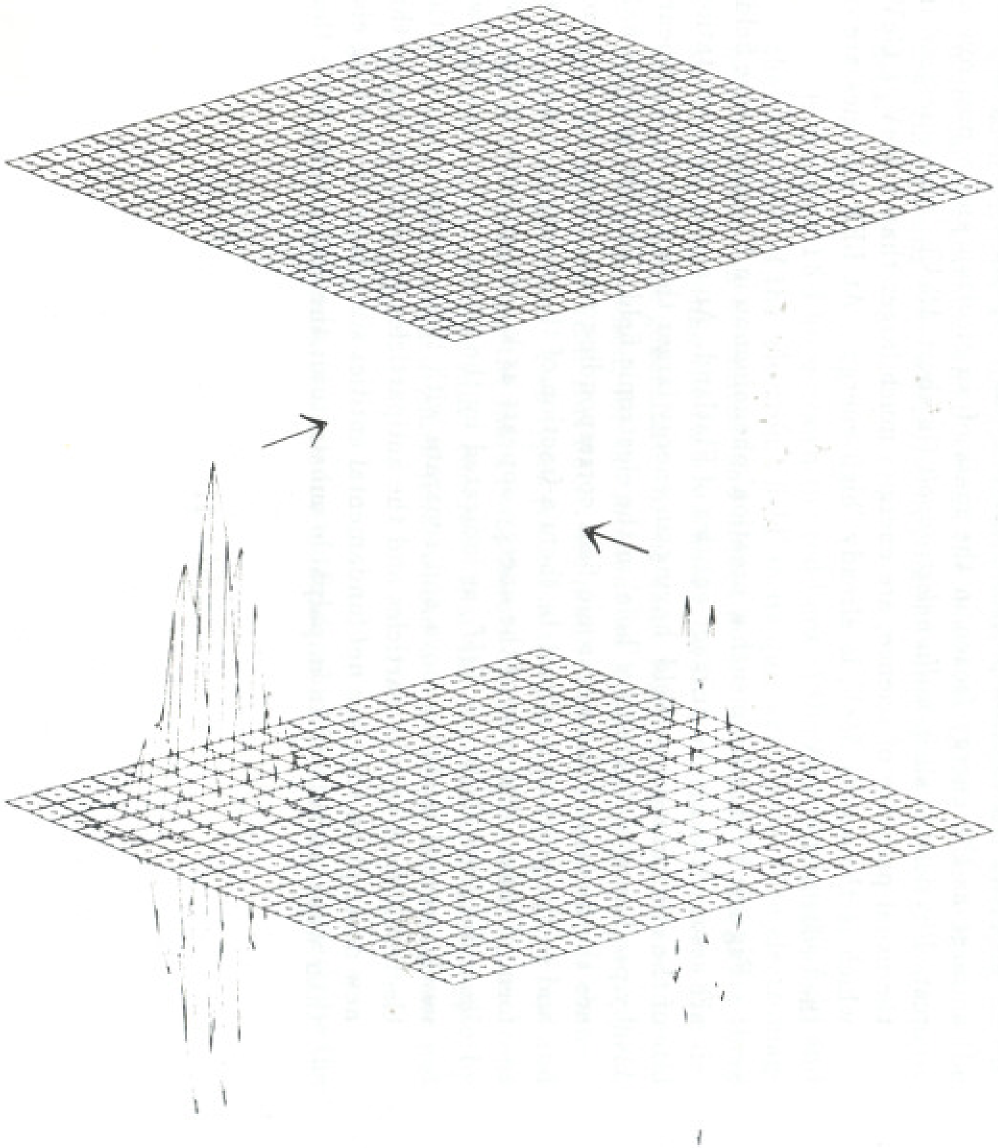


Fig.15 Two photons with a not excited electronic field

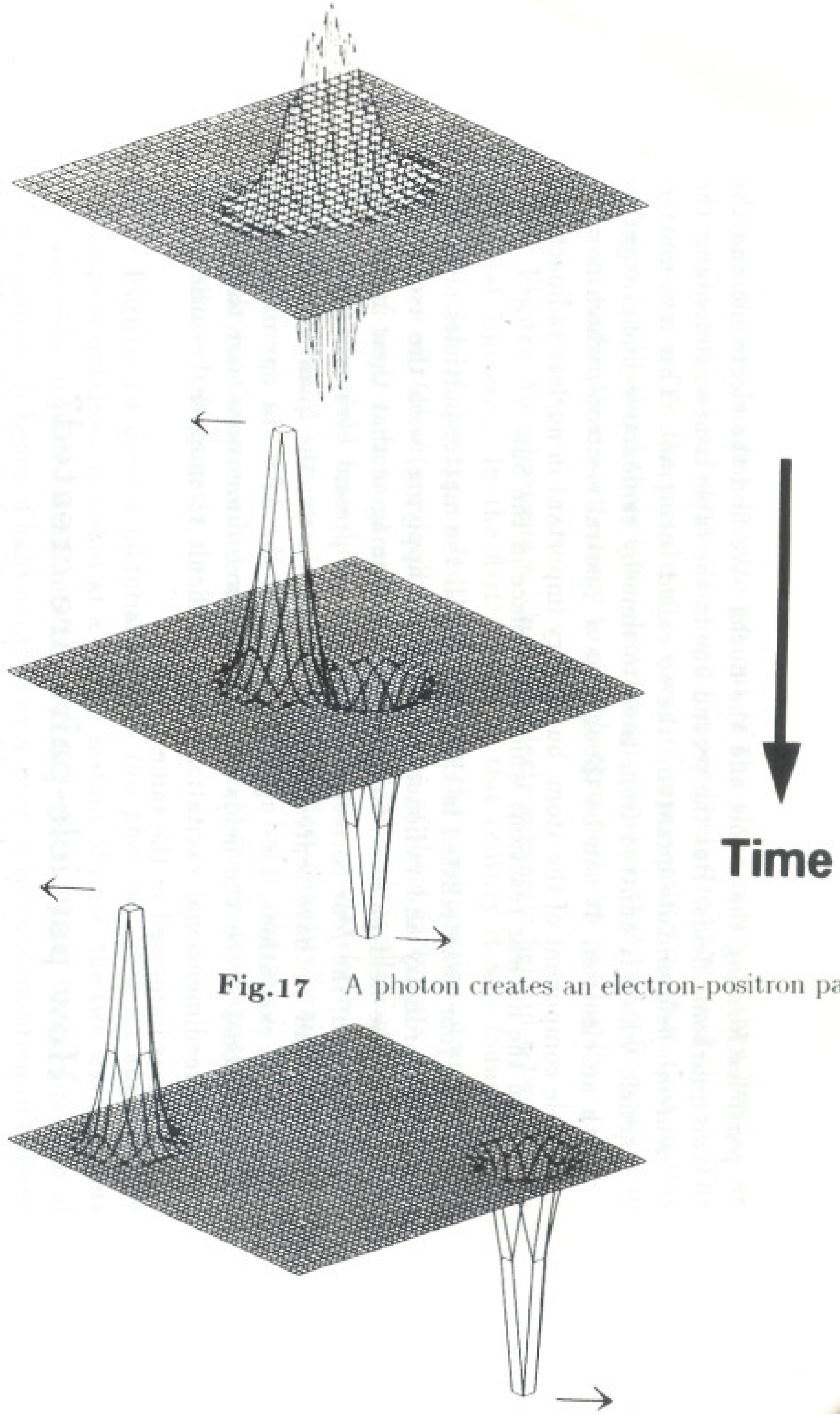


Fig.17 A photon creates an electron-positron pair

MATTER - PARTICLES

FIELD :	***QUANTUM :***
ELECTRON FIELD	e
NEUTRINO FIELD	ν
UP - QUARK FIELD	u
DOWN - QUARK FIELD	d

Fig.16 Matter-fields needed for making up the atoms

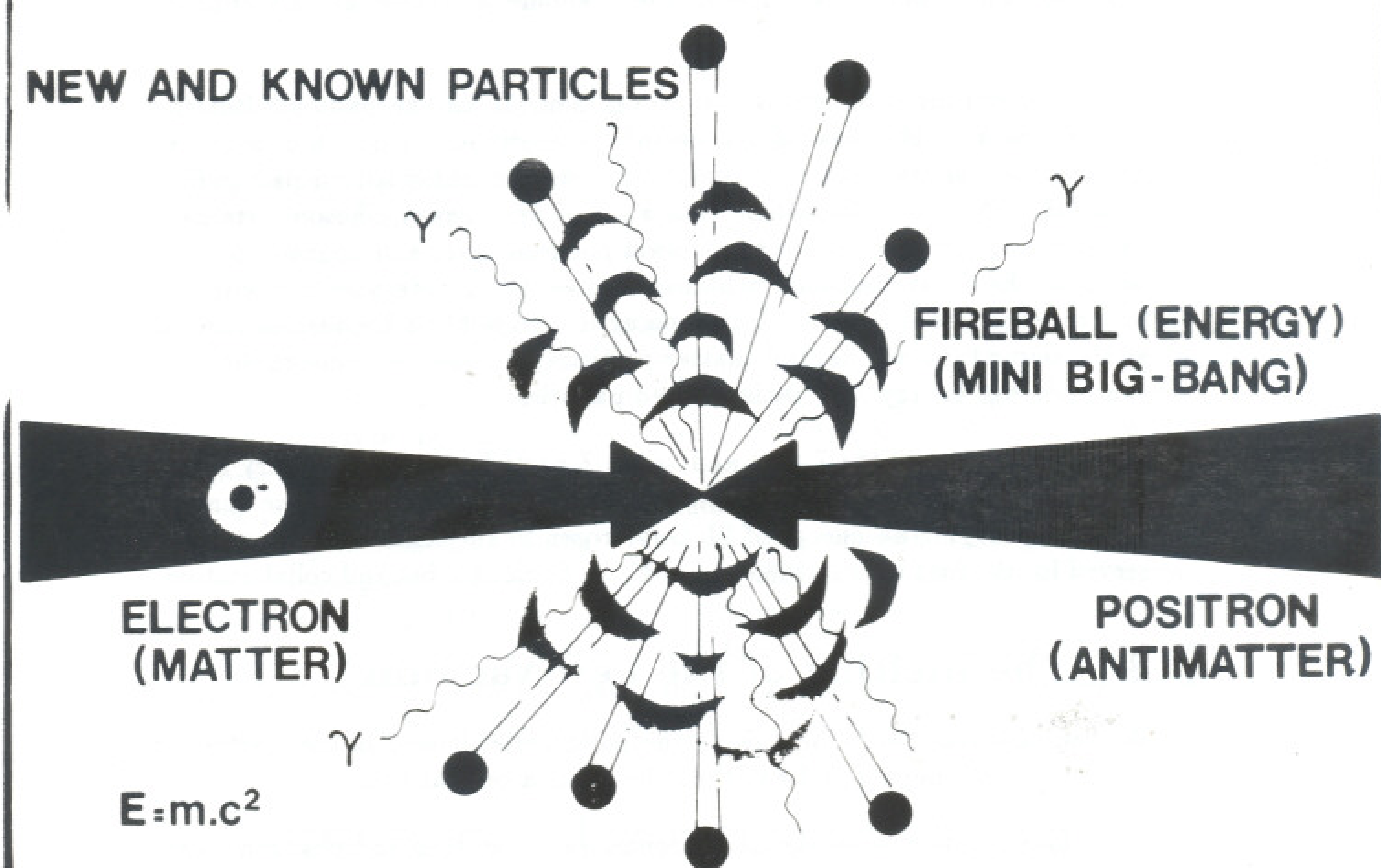


Fig.18 Corpuscular description of pair annihilation

the oscillations are *diffused in space*, so that particles are not in one point at a time, but rather span a finite region of space.

By inverting in the figure the arrow of time, we see a movie in which an electron and a positron collide, annihilate (when the hill fills the hole) and give all their energy to the electromagnetic field. Combining the two processes, first the annihilation and then the creation, the quantum of the electromagnetic field appears as the *necessary intermediary* through which an electron and a positron can either give up or obtain their masses and kinetic energies. For this reason the electromagnetic field is known as a *mediator-field*; its quanta, the photons, are the typical *mediator-particles.*

According to the *field picture*, matter-particles are the quanta of fields which can exchange energy with the photons, quanta of the electromagnetic field. The electromagnetic field is the most known *mediator*, through which energy exchanges among matter-particles can take place. But it is not the only oner. In the last fifteen years three other types of mediators have been discovered by using particle accelerators all around the world. I cannot even touch upon such a vast subject, and I limit myself to introduce the new mediator which plays a key-role in the phenomena studied at LEP: the so-called *Z-field.*

The quantum of Z-field is electrically neutral, as the photon. But the energy frozen in the mass of a Z-particle is enormous: as much as 91 GeV, about 90,000 times larger than the mass of an electron-positron pair (which is worth 1 MeV). A Z-particle is a kind of very heavy photon. Its field can exchange energy both with electron-positron pairs and quark-antiquark pairs, as the electromagnetic field does. [Moreover, it interacts also with the neutrino field, to which the electromagnetic field is blind because neutrinos, as the name says, are neutral matter-particles and the electromagnetic field can exchange energy only with charged particles.]

The existence of the Z-field and of the Z-particle, which is its very heavy quantum, was predicted in the sixties. The actual production of these quanta, each one carrying an energy of 91 GeV frozen in the form of mass, was observed for the first time in 1983 at CERN by Carlo Rubbia and collaborators.

8 The melting of the new vacuum

We can now start with the visit to the second site; indeed in the *melting of the vacuum* happening at LEP, the Z-field has a central role.

In four points around the LEP circumference electron and positron pairs, after having been heavily massified, annihilate and their total mass transforms into the [rest] masses and kinetic energies of newly created particles. **Figure 18** is the classical picture of such a phenomenon: two corpuscules, labelled e^+ and e^-, disappear and many others corpuscules come out in a process which is very mysterious. In fact one can legitimately ask: how do the elementary electrons and positrons (which have no extension and no memory) manage to 'know' which other particles can be created?

[The puzzle is illustrated by the next drawing. In **Figure 18b** the creation process is described as the disappearance of two energetic strawberries and the appearance of many fruits. How do the annihilating strawberries know which fruits exist in nature and can thus be created? How can this information be contained *inside* the strawberries? If the strawberries are point-like, as particles are, and thus have no structure the question becomes ever more difficult to answer. Where this information is contained? These are the questions that classical physics, which treats particles and corpuscules, cannot answer.]

In the field picture the explanation is instead simple, because *the memory of the laws of physics is written in the ever-present fields.*

The next figure (**Figure 19**) is the focal point of our discussion. It shows how the electron and the positron, by annihilating, pass over their energy locally to a mediator field, which gets highly excited. This *mediator field* excites in turn other matter-fields, which are present everywhere, so that a quark and antiquark pair, for instance, can be created in the reaction. The mediator-field is the go-in-between the annihilating particles and the created ones. I am sure that many of you have noted that in **Figure 19** the mediator field is drawn in green and *not* in red. The reason is that at LEP the Z-field is excited much more easily than the electromagnetic field because the electron and positron are massified up to a mass of 45.5 GeV each, so that in the annihilation 91 GeV are liberated; this is the exact energy needed to create a Z-particle. In this case the probability of the creation of the quantum Z is enhanced and the number of observable annihilation events is greatly increased. A similar '*resonance phenomenon*' takes place when a truck passing in the street causes a strong vibration of the glass of a window: the noise produced by the truck has exactly the same oscillation frequency of the glass, so that the energy is transferred with great efficiency from the vibration of the air to the glass. In this analogy the flat green net of the unexcited Z-field can be compared with the glass before the passage of the truck.

Let us summarise. In LEP the electron-positron annihilation puts energy

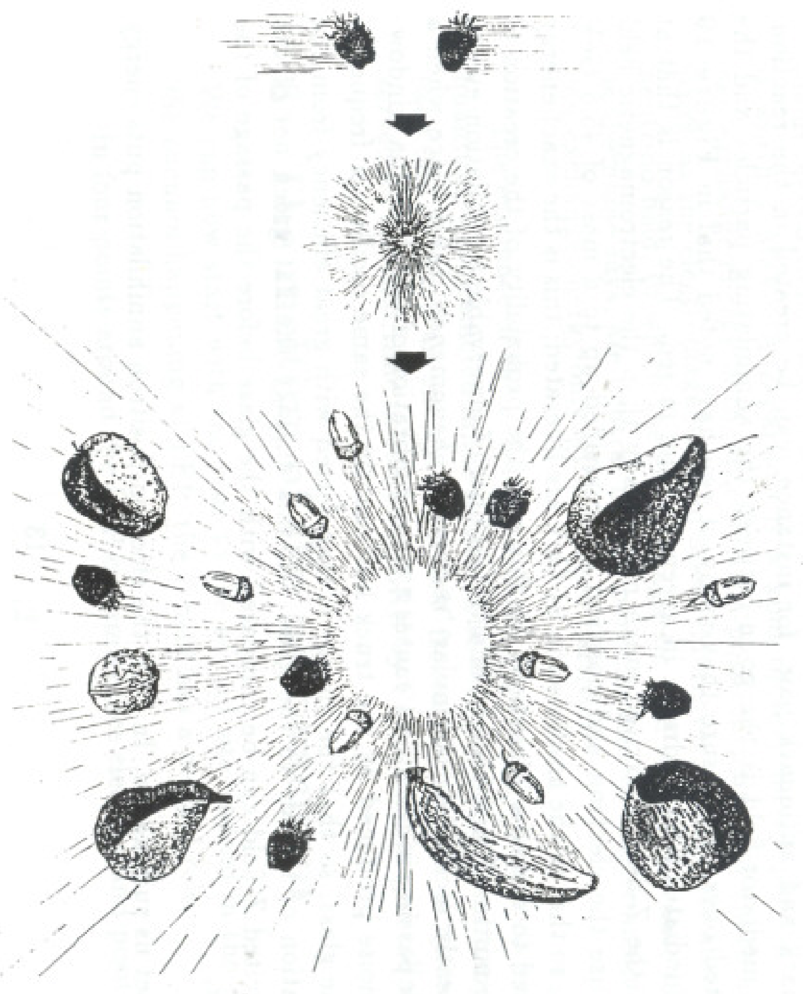
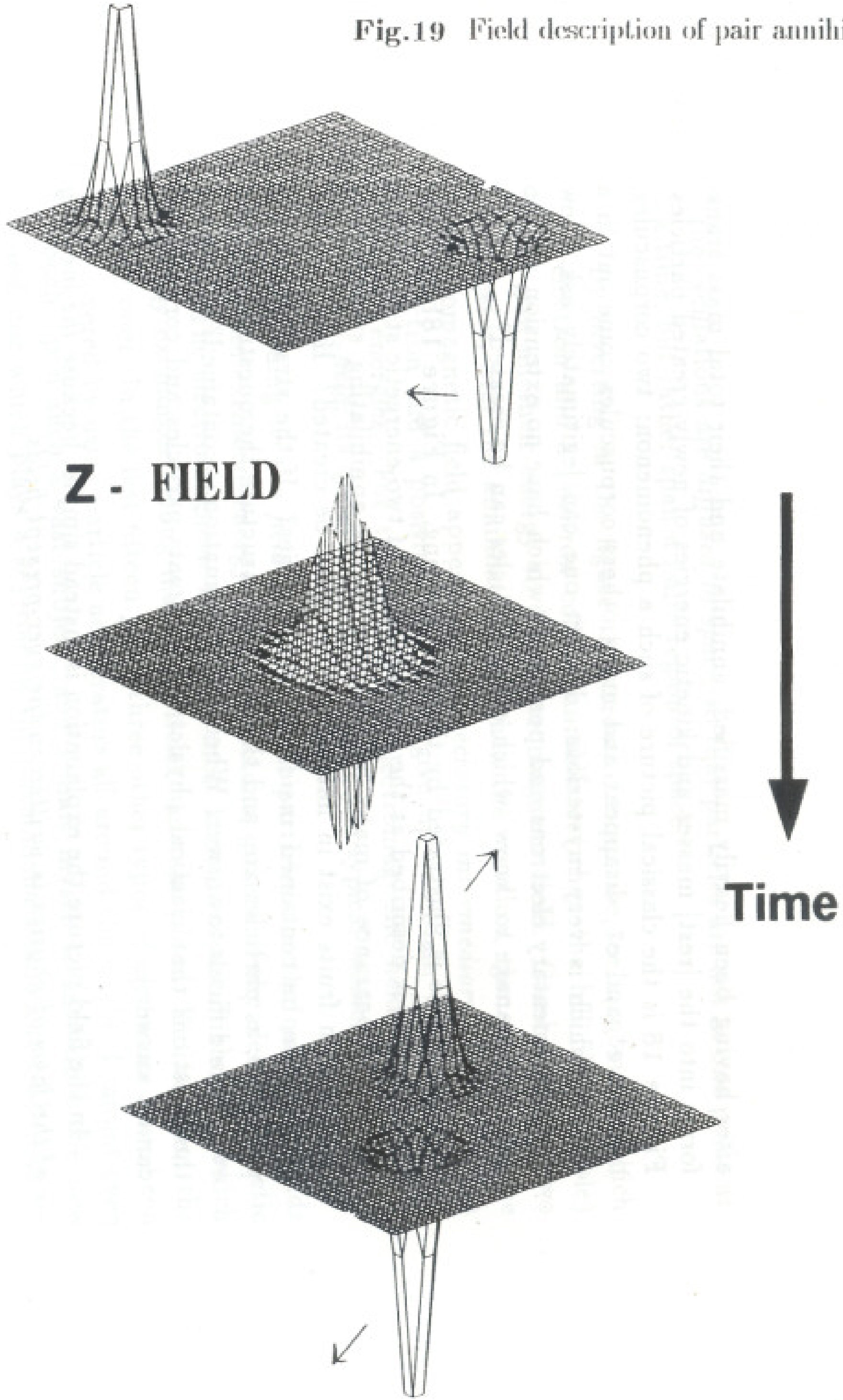


Fig.18 b Two strawberries by annihilation create new fruits

Fig.19 Field description of pair annihilation



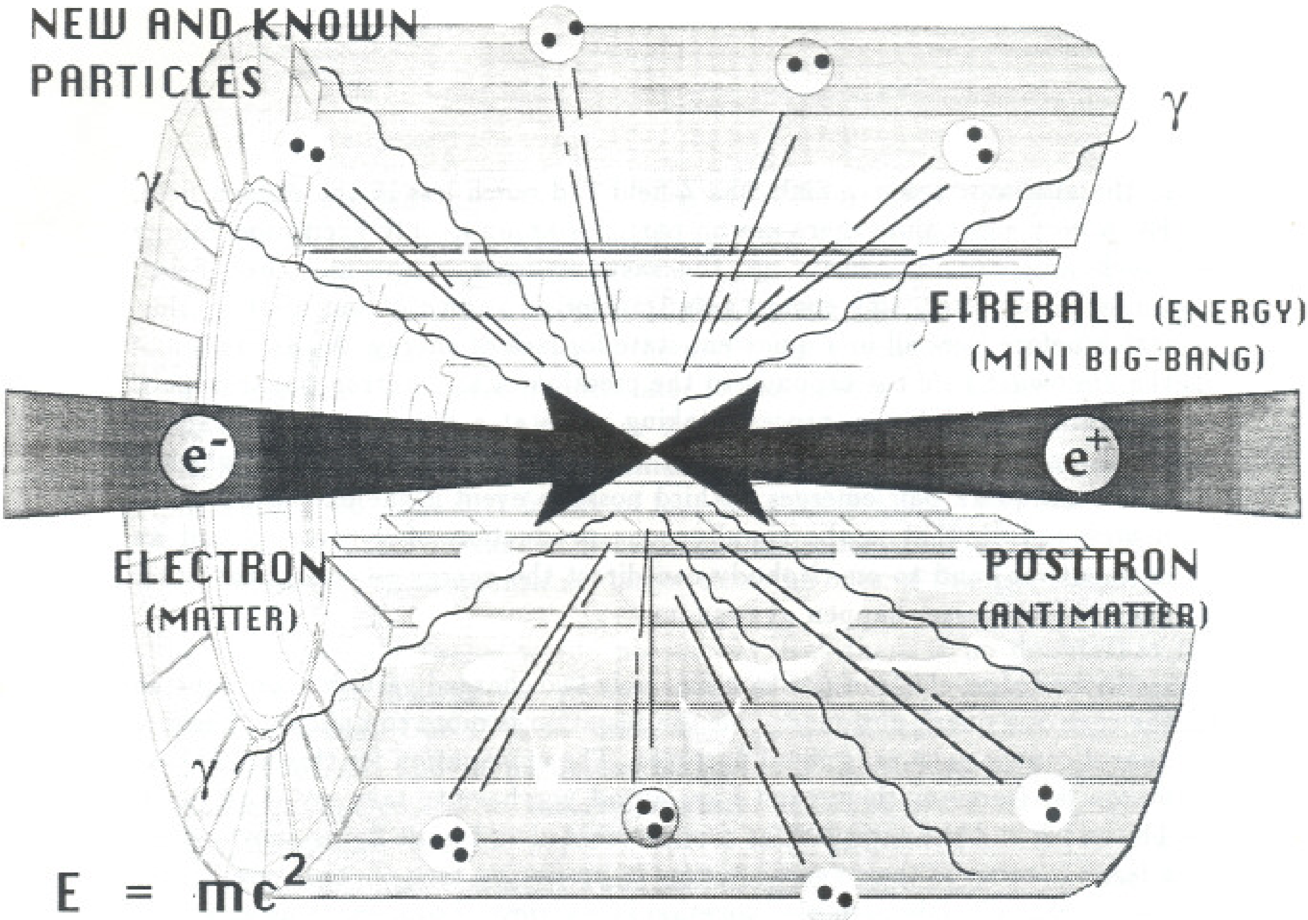


Fig.20 Corpuscular description of pair annihilation

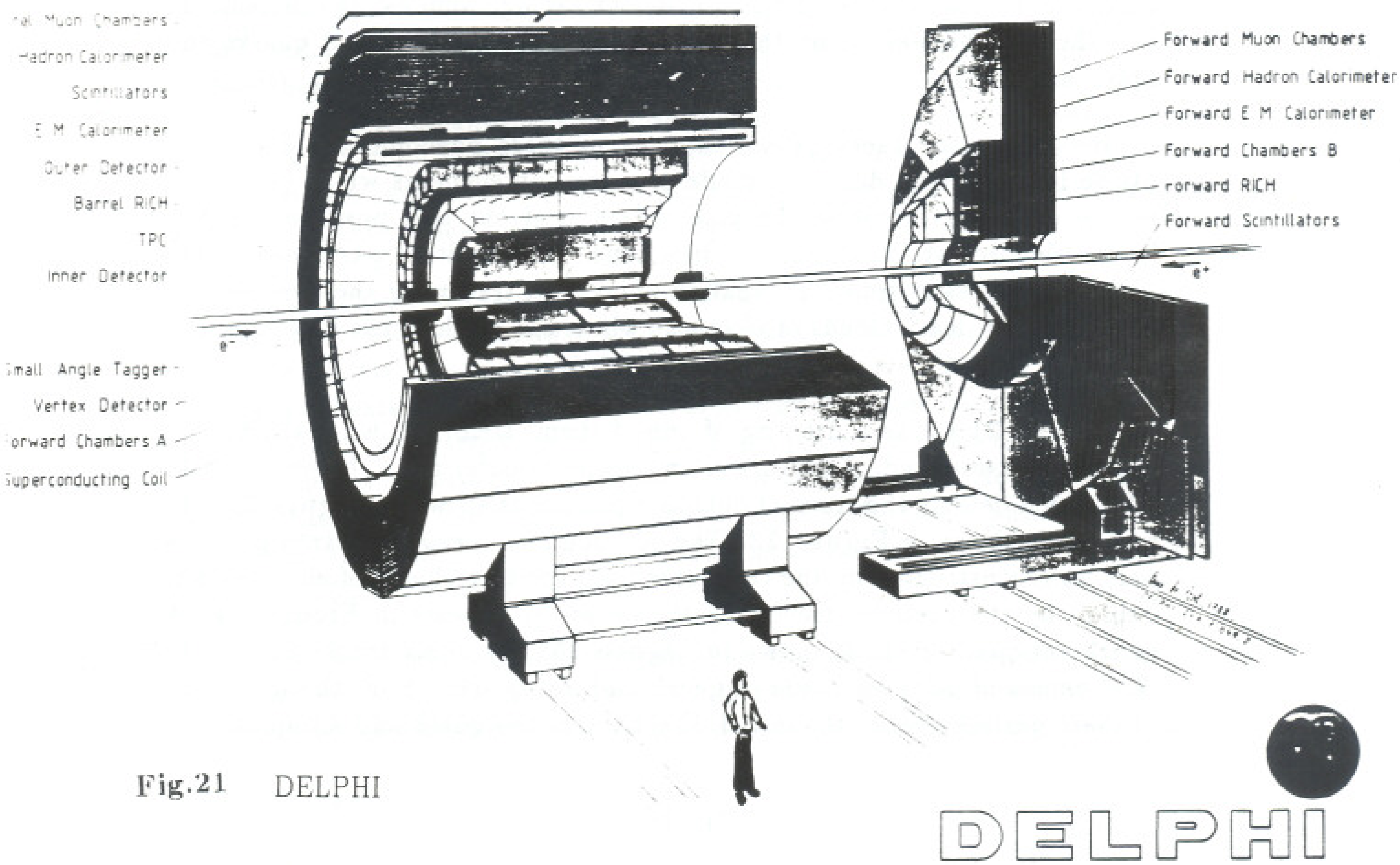


Fig.21 DELPHI

in the mediator fields, mainly the Z-field and much less in the photon field. For a very short time there are no particles around: only excitation energy which, one can say, 'heats up' the vacuum made of the unexcited fields. Immediately after, this energy gets transferred to one of the matter-fields, which before were all in a quiescent state for lack of energy. An excitation of the *electronic field* corresponds to the creation of an electron-positron pair. In another annihilation process (taking place at a later time), the excited mediator field hands over its energy to the *quarkonic field*, from which a quark-antiquark pair emerges; a third possible event is the excitation of the *neutrino field*, that is the simultaneous production of a neutrino and an antineutrino, and so on. Nobody can direct the energy to one or the other field; the processes happen at random.

In case of an electron-positron pair only two charged particles come out; in the case of a quark-antiquark pair the situation is more complicated because quarks cannot exist as isolated particles. The explanation for this would take us too far from our theme and I am afraid you have to take my word for it. The quark and the antiquark as soon as created and while flying apart, spend a large fraction of their kinetic energy in producing tens of other quarks and antiquarks, which in turn bind together in a variety of combinations and come out as charged and neutral *compound* particles. They are the small balls of the classical description reproduced in **Figure 20**. What is important is that there are *no* fields corresponding to the outcoming particles; as the neutrons and the protons making up the nuclei, they are combination of quarks and antiquarks.

How can one observe what happens in these phenomena? Physicists utilise large particle detectors made of many sub-elements which (as shown in the drawing) surround the pipe where electrons and positrons annihilate while circulating in opposite directions. The resultant particles and antiparticles fly away from the creation point and, traversing these cylindrical sub-detectors, leave clouds of electrons which can be detected by electronics means.

Figure 21 shows a drawing of one of them, DELPHI, with which I am personally associated. A picture of one of the cylinder-like subunits of DELPHI which detects the track of outgoing particle is shown in **Figure 22**. An end-cap is shown in **Figure 23**. The creation of a (heavy) electron-positron pair, as reconstructed by the computer from the tiny clouds of electrons left behind by the particles traversing the detector, appears in **Figure 24**. A quark-antiquark event is shown in **Figure 25**: the many tracks are due to the *compound* particles made of quark and antiquarks. Still, the directions of these particles recall the initial directions of the quark and antiquark.

There are four detectors working at LEP: ALEPH, DELPHI, L3 and OPAL. In the meeting which is taking place at the moment at the Royal Society we are discussing the outcome of the experiments performed by the four detectors. It will take too much to describe the many results obtained at LEP since August 1989, when the first annihilation were observed. Suffice it to say that only three months later it was proven beyond any doubt that in the physical vacuum there are *twelve different matter-fields*, which can logically be grouped in three *families* of four fields each. They are displayed in **Figure 26**. The first family of four we already know. The other two are similar, with two quarks, an electron-like and a neutrino-like quantum. But the masses of these quanta are larger than the ones of the first families.

Why exactly twelve we do not know. But there is no doubt that the technique for melting the vacuum used at LEP has brought very rapidly its first fruits. Due to it we know now somewhat better that the vacuum is everywhere, and in particular in the 1 m^3 box emptied of all matter-particles and cooled to the temperature of the absolute zero ($-273°$ C). From the naive realistic point of view I have adopted the box (even when emptied of all matter-particles and radiation) can be thought of as containing 12 unexcited matter-fields and many unexcited mediator-fields (including the electromagnetic and the Z fields) coupled together in such a way that, when available, energy can be transferred locally from one field to the other. Not every field senses every other one; for instance the quark fields 'feel' *all* mediator-fields, while the neutrino-field is much more insensitive. [In the box there is also a thirteenth field which acts on everything: the gravitational one. I left it aside until now because our understanding of it in relation to the subatomic world is still incomplete. But looking around in our Universe its importance cannot be denied and it is thought that soon it will be integrated in the quantum field picture.]

The field description of the annihilation phenomenon justifies the name given to this subject: *melting the new vacuum.* Indeed the energy liberated in the annihilation goes into the physical vacuum where all fields were initially nil and 'heats them up' to enormous energy densities with the consequent emission of new particles; this is similar to a piece of metal which, heated on a flame, melts because the atoms agitate more and more and detach themselves from each other. In the case of the vacuum fields, the quanta emerge and 'detach' themselves from the field while energy reappears as mass and kinetic energy of the produced particles.

The same phenomenon happened in the initial Big Bang. According to present theories, the energy *density* produced in LEP was available in the Universe *one tenth of a billion* of a second after the Big Bang. The

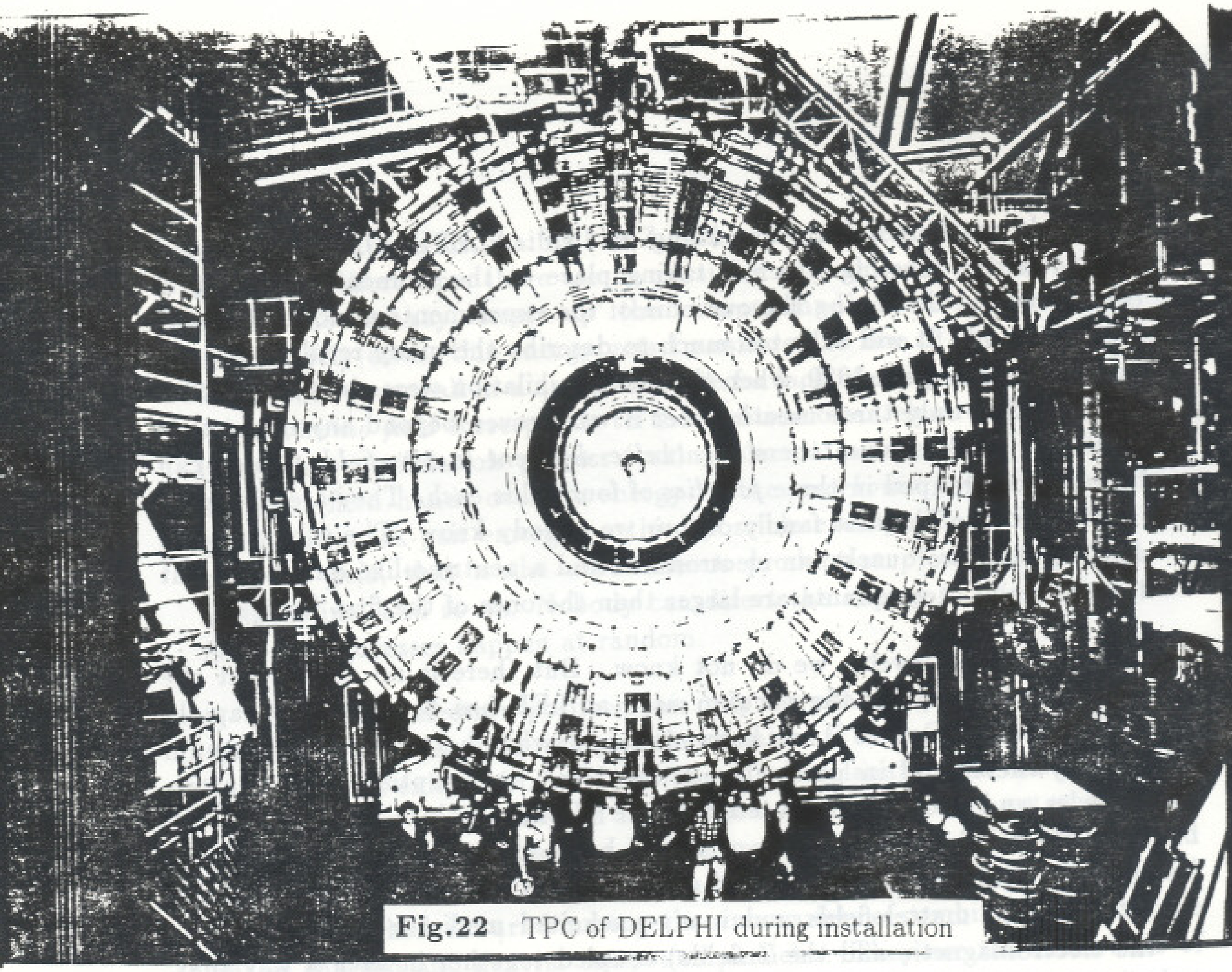


Fig.22 TPC of DELPHI during installation

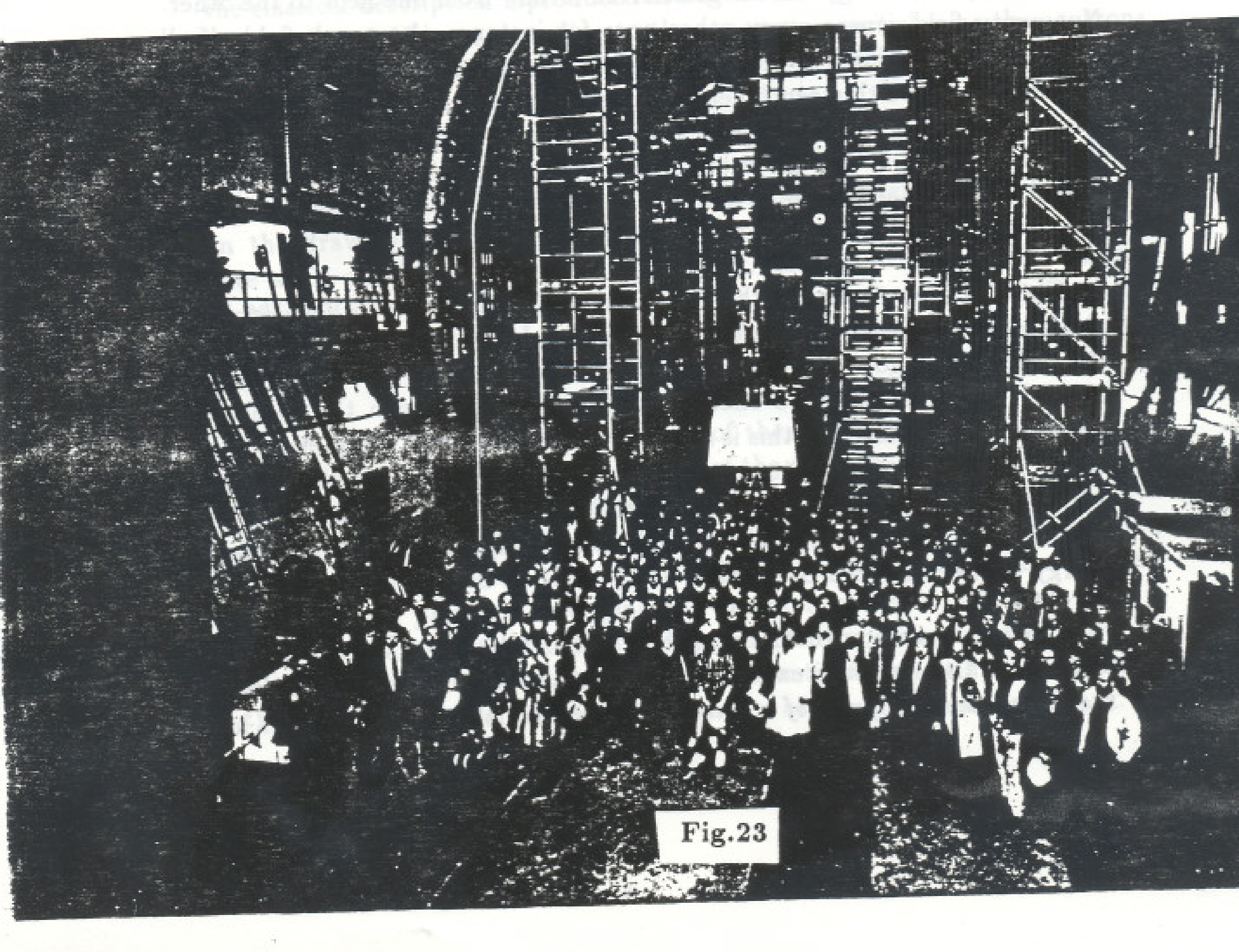


Fig.23

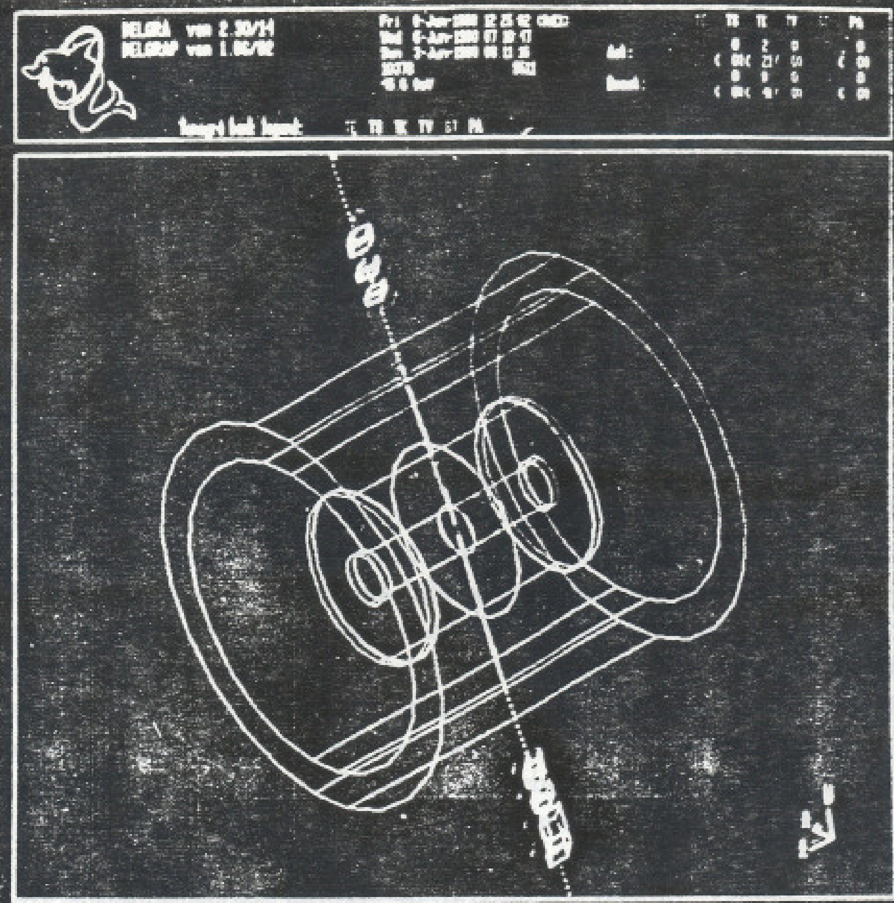


Fig.24 Tracks of $\mu\mu$

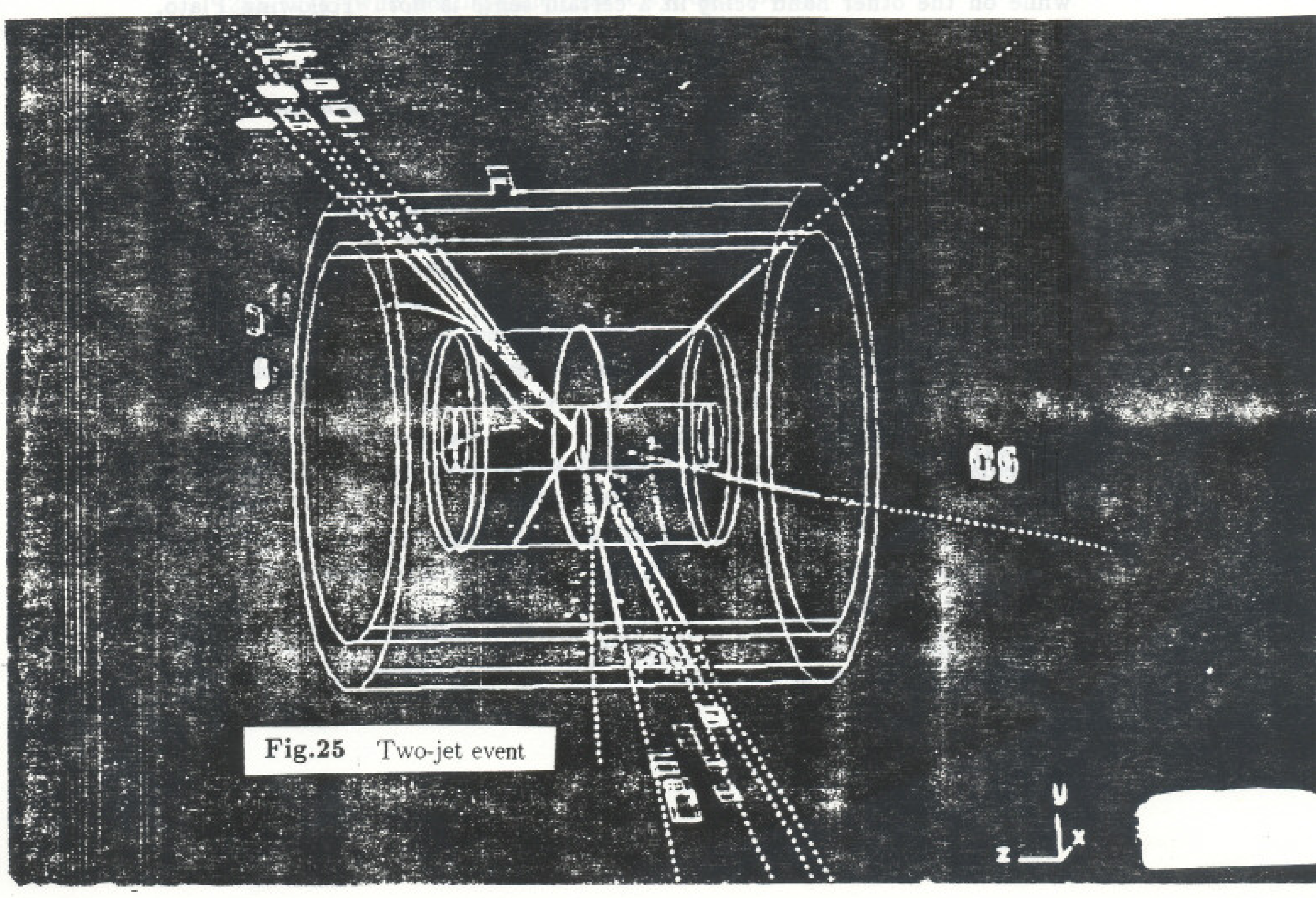


Fig.25 Two-jet event

corresponding temperature was a million of a billions degrees! At that time the expanding Universe was as large as our present solar system: the involved volume was much, much larger than the one heated by the electron-positron annihilation at LEP, but the reactions which were then taking place were the same we study today at CERN, the European laboratory, near Geneva.

9 Fields and the metaphysical non-being

The *quantum field picture* of the vacuum makes it very different from the non-being conceived by both Democritos and the 'classical' physicists. Matter-particles, the quanta of these fields, are also very different from the unbreakable, eternal greek atoms. Guided by many decades of experiments and of theoretical understanding, our ideas of the particles and the vacuum have thus grown much more sophisticated than the ones put forward by the first atomists. Indeed already Plato criticised them in the dialogue 'The Sophistes'. He started to move away from the concept of a physical non-being, which is an integral part of the world structure, to introduce the notion of 'logical' non-beings. Indeed wrong statements and wrong opinions are to be taken into account, and they are a sort of non-being. There exist also opposition which are negations of a way of being: the ugly is non-beautiful, the small is the non-big. Thus Plato stated 'both *non-being is* in a certain sense, while on the other hand *being* in a certain sense is *not*'. Following Plato, Aristotle recognised that 'non-being can be expressed in different ways' and distinguished *three* meanings of non-being. The most important to us is the non-being which is *potentiality*, as opposed to being which is *actuality*. Here a new notion appears: the metaphysical nothing is not the absolute nothingness, but contains the germs of a development towards becoming actual. [The other two meanings of non-being from Aristotle are the ones of Plato: the *categorical* one (non-big) and the *falsitative* one (false statements). Later *stoicists* underlined that non-being is any way something because we, as a minimum condition, think it and talk about it.]

Neo-platonists developed further the above ideas going back to the atomist inspiration of linking the nothing to physical reality. The best known of them, Plotinos, lived in the third century of our era. He followed Plato's intermediate position between the being and non-being by distinguishing two meanings.

(i) Non-being in the primary sense is *matter*, which is not absolute nothingness but is *different* from the being because in itself it is nothing but potentially everything.

(ii) The second meaning is the *One*, which is pure non-being. The One is *before* every being, is the originator of everything and cannot be uttered.

For Plotinos, the overall movement from the One to matter gives rise to actual being, which matter by itself seeks in vain to attain.

It seems to me that the neoplatonic view is the one that, in the history of western philosophy, got closer to today conception of the relation between the vacuum and the physical reality represented by particles. I would compare the non-being as matter with the all pervading fields of quantum theory; indeed the fields are not matter, but their presence determines potentially the nature of the matter-particles which we directly observe. More controversial is the identification of the One of Plotinus. For a materialist the One could be energy, liberated during the Big Bang [maybe at the expense of gravitational energy]; it is in fact the energy which causes the quanta, elementary wave packets of the fields, to emerge from the fields and appear to us as matter-particles. Particles are the actual matter which now forms stars, planets and our bodies. For a spiritualist the One could be identified with God, who used energy as an instrument to extract from the fields the material background necessary for the development of life and, later, of conscious free wills.

Starting with the middle ages, the discourse on the non-being moved farther and farther from the preoccupation of understanding the origin of physical reality. One of the last systematic views which was still preoccupied with the problem of justifying physical reality, is that of Thomas Aquinas (1255-1274) who distinguished three types of beings:

(1) *natural beings*, objects which exist in nature;

(2) *intellectual beings*, as the mind, its concepts and so on;

(3) *divine beings*, in primis God and then his love, the angels and so on.

By negating these beings he obtained three categories of non-beings:

(1) *natural non-beings*, which exist in our mind but which do not exist in nature such as centaurs;

(2) *privative non-beings*, obtained by negating a concept, as darkness in opposition to light;

(3) *matter* which, being the negation of divine *beings*, is not (as neoplatonists thought) but is as potentiality. This is the point which interests us today.

From these categorisation Aquinas, and with him most of the christian theologists, came to the conclusion that the *divine being* (i.e. God) created the *natural beings* from *the nothing*, which is matter in its potentiality (creation ex nihilo).

Later the philosophical reflections on the nothing subdivided into three main streams, thus completing the divorce of metaphysics from physics. The *logical stream*, which started in the middle ages with Anselm of Canterburry (1032-1109) and William of Ockham (1285-1349) and had in Kant a strong advocate. The *mystical stream*, whose roots can be found in the Jewish Kabbala, the mystical approach claimed that man, to get closer to God, has to move towards the nothing. Hegel belonged in a certain sense to this stream, since for him the first task of philosophy is to know the absolute nothing. Finally, the *nihilistic stream*, which brings us to Sartre and to the 'anxiety (Angst) which reveals the nothing' of Heidegger.

Words and concepts change along the times; scientifically minded people tend to discard as empty phantasies the views of the thinkers of the past. Still, I hope that this short account of the battles around the obscure idea of the nothing can provoke some thoughts about our own way of considering the results of concrete physics experiments and their interpretation in terms of physical vacuum. At the same time I am convinced that the field description and its unsuspected richness, which I will unveil even more in a moment when talking about the fluctuating vacuum, may inspire the philosophers who still use the concept of non-being.

10 The fluctuating vacuum

This richness has its roots in the discovery made in the 20's by a young German theoretical physicist, Werner Heisenberg, who is shown in **Figure 27**. By analysing the new situations which arises in any attempt to describe the atomic and subatomic world, he was obliged to conclude that the fundamental conservation laws of classical physics can sometimes be evaded. In particular, energy conservation (the main pillar of physics) does not *always* hold. This can shock, but it is a fact that has been by now demonstrated experimental consequences.

Energy can be either extracted from nothing or disappear into nothing. But such a local imbalance is possible if, and only if, it takes place in a very short time and is quickly healed so that it cannot be directly detected. The idea of the momentary and unobservable suspension of the energy conservation law was not easily accepted by physicists. But a lot of experimental results, which we cannot discuss here, point in one and the same direction. The laws which seem to govern the subatomic world are much less constrained than the ones of classical physics; among the new degrees of freedom we have already met the fact that particles, being wave packets, while moving are *not* in a definite point but instead are diffused in space. Non-absolute energy conservation is another consequence of the somewhat fuzzy behavior of the subatomic world.

Its consequences on the idea of the vacuum are striking. Even when there is *no* energy in our box, the matter-fields and the mediator-fields are not nil for ever. By itself, without any cause, *excitations of the fields can appear here and there.* These quanta have an ephemeral life, because otherwise the energy conservation law would be violated for too long and could be directly detected; for this reason they are called *'virtual quanta'*. Still photons appear and disappear together with virtual electron-positron pairs, as pictorially described in **Figure 28**. It is this continuous agitation of shortly lived virtual particles that makes the vacuum much richer than the superposition of many inert fields. We have to do *not* with a static system, but with a dynamic structure in continuous random movement, with a *fluctuating vacuum.* Imaginatively, I can say that the momentary virtual particles which vivify the physical vacuum are a kind of froth without sea.

Time is getting short, but I must at least mention that here the *naive realism* I have taken for granted until now meets a very serious difficulty. How can we speak of fluctuations which cannot be observed and happen in an empty box at zero absolute temperature? If we put something there, to observe the vacuum, the box is no longer empty and, so, what can we conclude? As anticipated, there is no answer to these questions; but we at least know experimentally that vacuum fluctuations have *measurable effects* in phenomena in which we do not experiment on the 'nothing', but on very simple systems, as an *hydrogen* atom.

[In the case of this atom, made of a proton and an electron, the creation of virtual electron-pairs influences the overall energy of the electron. The phenomenon is shown in **Figure 29**, where the fact that the proton at the center of the atom has a positive charge is pictorially represented by the red lines of the electromagnetic field being statically pulled down by the yellow proton. In this distorted static field the atomic electron, which encircles the proton and is not shown, has a certain energy. This energy however is modified by the appearance and disappearance of virtual pairs of electrons and positrons, shown in the figure; there is no agreement with the measured energy of the electron if this effect is not taken into account.

Just after the war the experimental confirmation of this effect eventually crowned quantum field theory, which stipulates that the fundamental quantities in physics are the fields and not the particles, and that these fields continuously fluctuate, even when their overall energy content is exactly nil.]

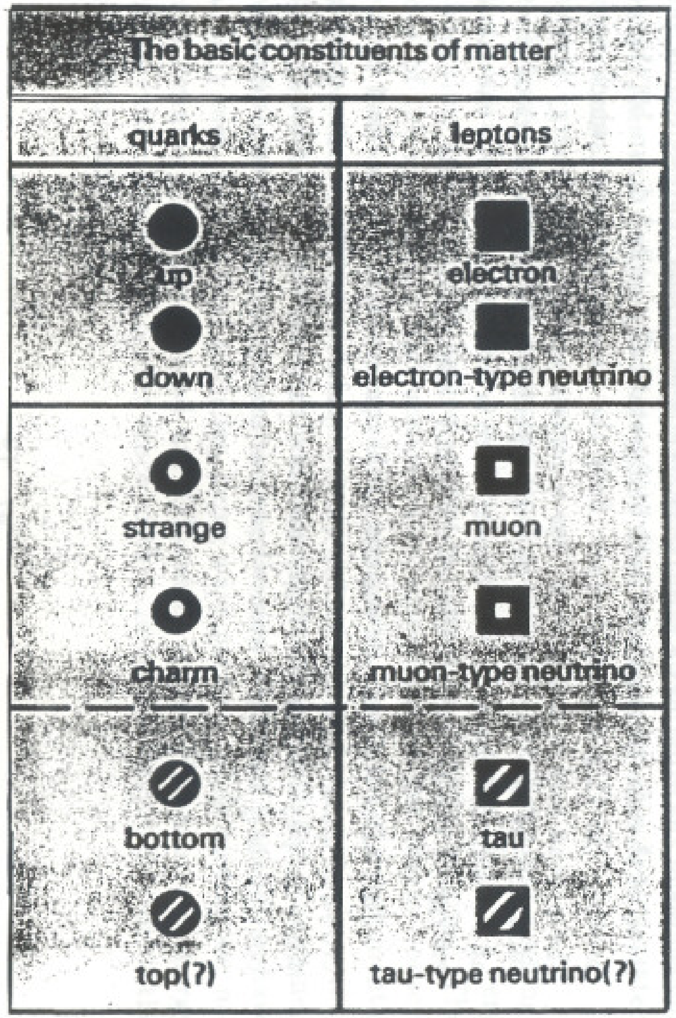


Fig.26 Three families of matter-particles

Fig.27 Heisenberg

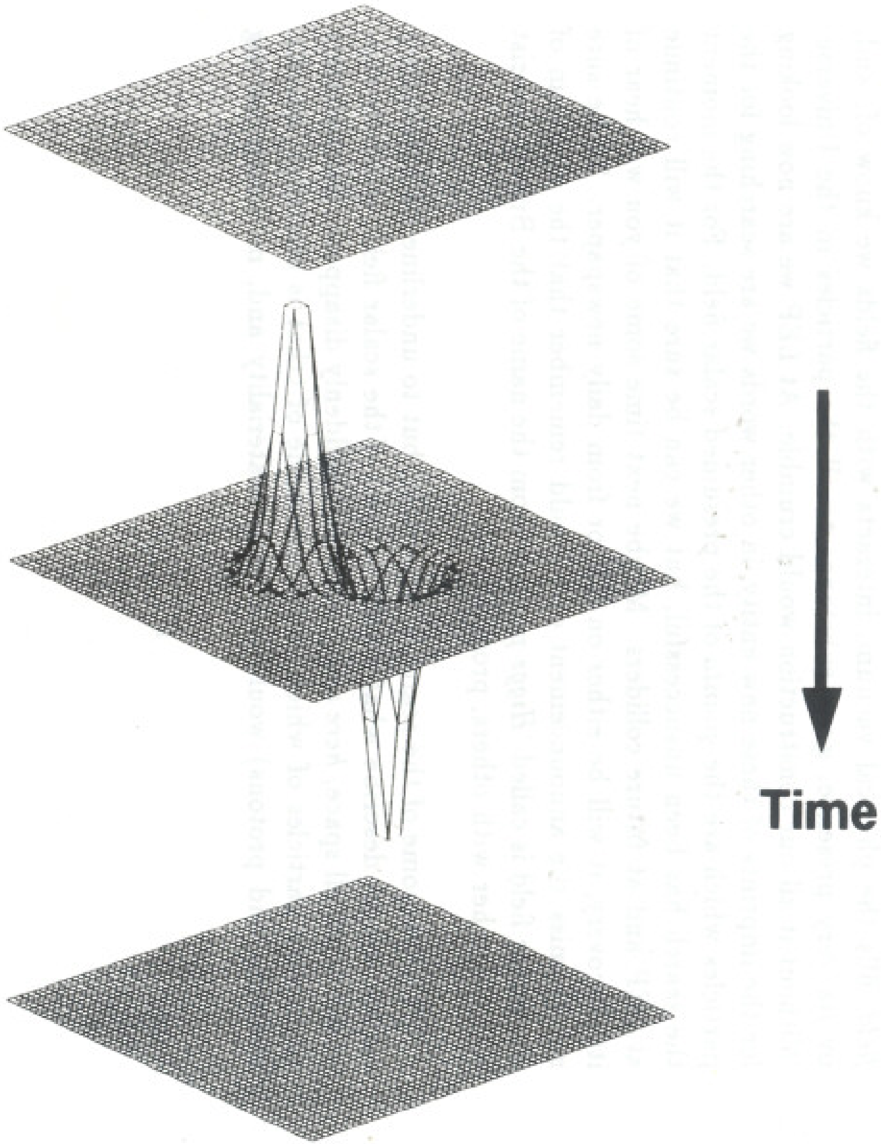


Fig.28 Field description of virtual pair creation

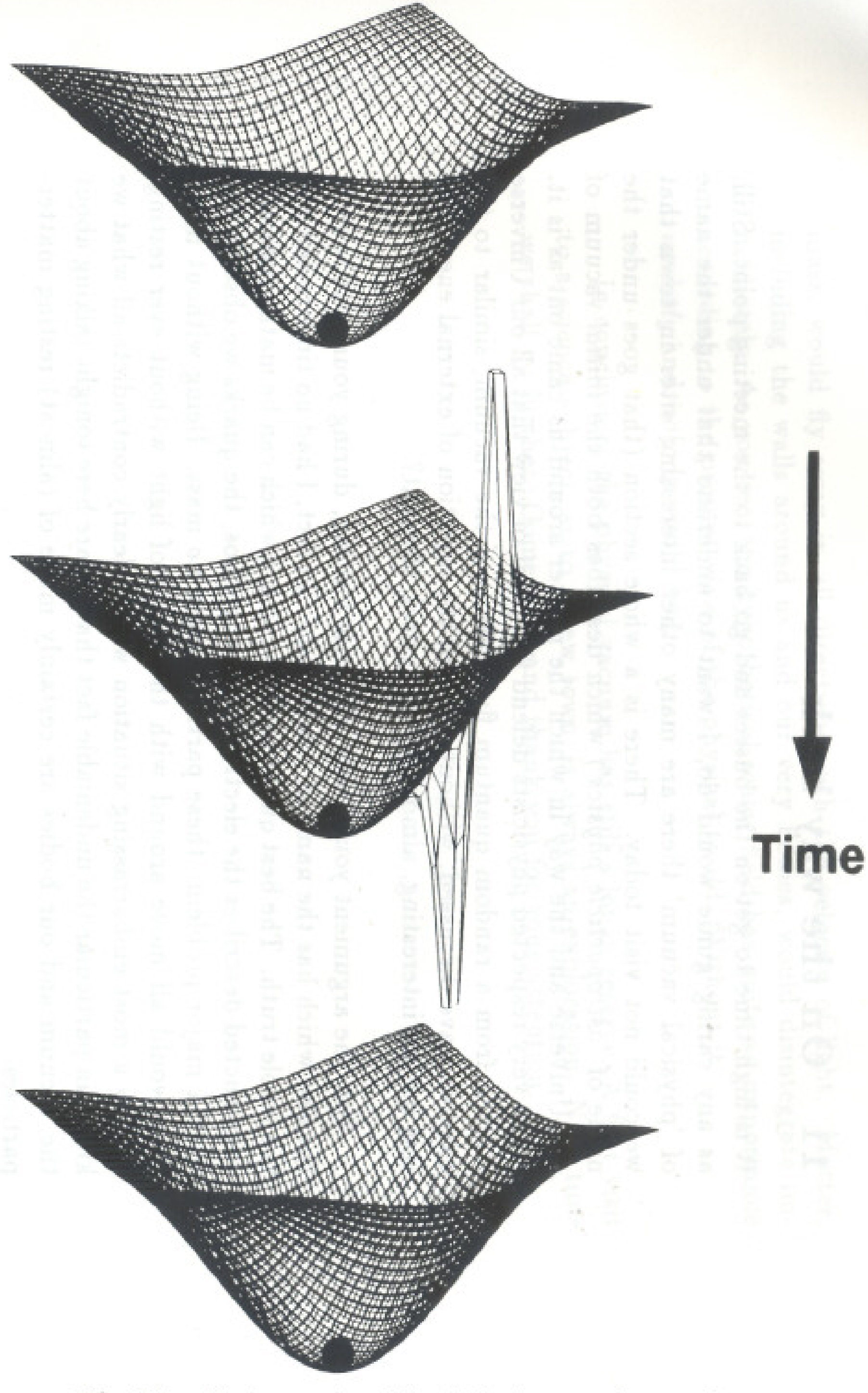


Fig.29 Proton and a virtual electron-positron pair.

11 On the way back

It is high time to get on the busses and go back to the meeting point. Still, as any caring guide would do, I want to underline that under the name of 'physical vacuum' there are many other interesting sites in town that we could not visit today. There is a whole section (that goes under the name of '*astroparticle physics*') which describes both the *initial* vacuum of our Universe and the way in which the matter around us came out as is it. Some very respected physicists defend the point of view that all our Universe started from a random quantum fluctuation of the vacuum, similar to the ones we have discussed, without needing the injection of external energy. Is this not an interesting, almost metaphysical, thought?

But the argument you should not miss visiting, during your next tour, is the one which has the name of '*scalar field*'. In fact, I had no time to tell you the whole truth. The best quantum field picture which can be mathematically constructed describes the electrons, the neutrinos, the quarks we observe but with a major problem: these particles carry *no* mass. Being without mass, they would all move around with the speed of light without ever resting. This is a most embarrassing situation which clearly contradicts all what we know, in particular the undeniable fact that we are here tonight talking about the vacuum and our bodies are certainly made of (almost) resting matter-particles.

How to give substance to the quanta of all the fields filling the Universe? Today the generally accepted idea is that at least one new field called *scalar field*, fills the physical vacuum, interacts with the fields we know of, and, by its very presence, gives substance to all the particles in the Universe. Without it all our construction would crumble. At LEP we are now looking for the imprints of these new entity, in other words we are searching for the particles which are the *quanta* of the presumed scalar field. For the moment the search has been unsuccessful, but we can be sure that it will continue at LEP and at future colliders. Maybe next time some of you will hear of its discovery, it will be either on TV or from daily newspaper. To be sure not to miss the announcement one should remember that the quantum of the scalar field is called '*Higgs particle*' from the name of the British theorist who, together with others, proposed it.

[The outcome of the search is uncertain, but to underline its importance let me simply describe what would happen *if* the scalar field, which is supposed to fill all space, *here* and *now*, would suddenly disappear. Immediately all matter particles of which atoms are made of (that is electrons, quarks, neutrons and protons) would lose their materiality and, no longer having

mass, would fly away in all directions with the velocity of light. Matter, including the walls around us and our very bodies, would disintegrate immediately. As you see, the hypothetical scalar field has quite an importance according to the present view of the physical world. Without it,
no body and *nobody* would be.]

In conclusion, the physical vacuum has still a lot in reserve. A first visit to a science subject, as to a new town, is always an exploration. Next time we shall go further. Come back and thank you for your attention.