Commemoration of Paul Dirac

Antimatter

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"Physical laws should have mathematical beauty"
P.A.M. Dirac, 1955

I have already gray hair but I belong to a generation which grew up in physics calculating Feynman graphs and using the CPT invariance of Quantum Field Theory. The world would look very differently if we would reverse the flow of time (an operation denoted by T),inverse all directions in space (an operation denoted by P) and change all particles into their antiparticle (an operation denoted by C). Yet the laws of physics would remain the same and all phenomena would occur in the same way. Our present understanding of physics implies the existence of antimatter and all ther properties of antimatter are predictable from the known properties of matter. All this looked so powerful, so beautiful and almost so natural to us, as we were learning modern physics in the late fifties and early sixties. The two ways to read the same simple Feynman graph, using it to describe, for instance, either the exchange of a photon between two electrons, or electron-positron annihilation and formation through one photon, looked like an obvious part of the calculation rules. This is shown in figure -1. One can read it horizontally. This is scattering. One can also read it vertically. This is annihilation and pair formation.The same term can be used to describe both processes.
When the discovery of the antiproton was announced, in the mid-fifties, it was perceived by those of my generation more as an expected event than as a breakthrough. Antimatter had already lost its mysteries! To each known particle one has to associate an antiparticle with the same mass and the opposite internal quantum numbers -those not associated with kinematical properties- and the rules followed by the latter are fully determined by those followed by the former. Together with relativity and quantum mechanics, antimatter was part of the general framework in which to work when facing with enthusiasm the exciting perspectives of modern physics.

1. Antiparticles, the legacy of Dirac

The conception of antimatter

Conceiving antimatter was, however, not such an old achievement and, if I listed antimatter next to relativity and quantum mechanics, it is because Paul Dirac, in his masterful combination of quantum mechanics and relativity, came to the conclusion that it was an unavoidable necessity. This was in 1929-1930. At that time it created a stir among physicists and the proton was even considered for a while as the

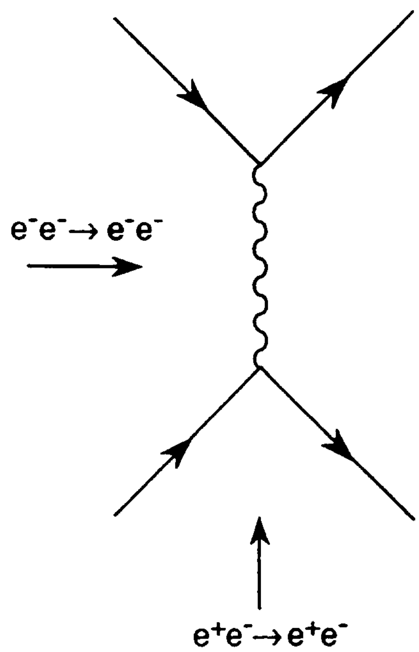


Figure 1: Feynman graph for lowest order electron-electron scattering (left-right) and for electron-positron annihilation and formation (down-up).

candidate for the still elusive particle with a positive charge which had to be associated with the electron as its antiparticle. However, this idea had to be quickly disregarded. Indeed Dirac first considered that possibility, saying later: "I just didn't dare to postulate a new particle at that stage, because the whole climate of opinion at that time was against new particles". But, by 1931, it was clear that this was not tenable and he then summarized the situation saying: "This would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge as the electron. We may call such a particle an anti-electron". And, he added at that time: "We should not expect to find any of them in nature, on account of their rapid rate of recombination with electrons, but they would be produced experimentally and in high vacuum they would be quite stable and amenable to observation". Dirac was right on all counts. The electron cannot exist without its positron counterpart. The discovery of the positron by Carl Anderson, in 1932, vindicated Dirac's electron theory. The positron, first seen in cosmic rays, by Anderson and soon afterward by Blackett and Occhialini, was there, as the anticipated antiparticle of the electron, with the opposite charge and the very same mass. Before long it was recognized as an active participant in the ß decay of radioactive nuclei. I was fortunate to have Gian Carlo Wick as my thesis adviser. He was the one who showed that the ß+ emission discovered by Joliot-Curie, whereby a positron is produced was also included in Fermi Theory of ß decay first formulated for the emission of electrons.

One soon learned how to create large quantities of positrons, appearing in association with electrons in the interaction of radiation with matter. Radiation freely turns into matter and antimatter and matter and antimatter freely annihilate into radiation.

I wish to follow here the presentation given by Dirac at the 7th Solvay Council, in 1934. It was actually originally presented in a beautiful and precise French. It starts with a magnificent sentence:

> "The recent discovery of the positively charged electron or positron has revived interest in an old theory about the states of negative kinetic energy of an electron, as the experimental results that have been obtained so far are in agreement with the predictions of the Theory".
>
> Figure 2 shows the first page of the draft (in English) which Dirac wrote for his Solvay article.
>
> The theory was not that old!

The presentation goes on explaining that, in relativity, negative energies readily come into the picture since it is the square of the energy, together with the square of the momentum, which makes up an invariant. In classical physics, where energy varies in a continuous way, one can still separate the positive energy domain, where the full energy exceeds the mass energy, from the negative energy one, where the full energy is less than minus the mass energy, but, in quantum physics, jumps between the two domains are allowed and they can no longer be separated. Dirac goes on in his specific style saying: "Under such circumstances two possibilities remain open: either there is a physical meaning for the negative energy states or we have to admit that the relativistic quantum theory is not correct". He later goes on saying that "A negative energy electron is an object foreign to our experience but, when considered in the framework of the electromagnetic theory, it behaves just as a positive energy electron having charge +e instead of -e. Yet one cannot identify it with a positron since positrons have positive energy".

Theory of the Positron

by P. A. M. Dirac.

The recent discovery of the positively charged electron or positron has revived interest in an old theory about the negative states of negative kinetic energy of an electron, as the experimental results that have been obtained so far are in agreement with the predictions of the theory.

The question of negative kinetic energies arises as soon as one considers the motion of a particle according to the principle of restricted relativity. In non-relativistic theory the energy W of a particle is given in terms of its velocity v or its momentum p by

$$W = \frac{1}{2}mv^2 = \frac{1}{2m}p^2,$$

which makes W always positive, but in relativistic theory this formula must be replaced by

$$W^2 = m^2c^4 + c^2p^2$$

or

$$W = c\sqrt{m^2c^2 + p^2},$$

which allows W to be either positive or negative.

One usually makes the extra assumption that W must always be positive. This assumption is permissible in the classical theory, where variables always vary continuously, since W can then never change from one of its positive values, which must be $\geq mc^2$, to one of its negative values, which must be $\leq -mc^2$. In the quantum theory, however, discontinuous changes of a variable may take place, so that W may ~~then~~ change from a positive to a negative value. It has not been found to be possible to set up a

4. Dirac's ms for the 1933 Solvay Conference

Figure 2: The draft of Dirac (in English) for his presentation (in French) at the 1934 Solvay meeting.

The solution which he then presents relies on the use of the exclusion principle of Pauli. He says "Let us accept that in the Universe as we know it, almost all the negative energy states are occupied and that the resulting charge distribution is not detectable because of its homogeneity over space. In such a case any unoccupied state represents a disruption which breaks this uniformity. This appears as a hole and it is possible to admit that these holes are positrons. The exclusion principle of Pauli states that any dynamical state available to an electron can be occupied by at most one particle. An electron cannot therefore loose energy while falling into a lower energy state which is already occupied.

This resolves the difficulties associated with negative energies since a hole in the distribution of the negative energy electrons appears as having positive energy. The hole reacts to an electromagnetic field as a positively charge electron of positive energy and with the same mass as the electron.

The article goes on in discussing quantitatively all the consequences, including pair creation and electron-positron annihilation, comparing them with available experimental information, and, in particular showing why a positron has a good chance to cross Anderson's chamber before annihilating against an electron. It continues with vacuum polarization effects.

The negative energy problem had been solved. A brilliant prediction had been made and verified. The price to pay was that the vacuum had become rather complicated. Following Dirac's approach the vacuum indeed behaves in many ways as a semiconductor, where electrons can be excited out of a filled valence band while leaving holes. This vacuum problem has now been solved but , as we shall see, other problems have come up. In any case Hole theory remained the standard way to calculate for many years and the complicated vacuum was not much of a philosophical problem.

In physics we are even getting used to complications of the vacuum. Today the vacuum of the Electroweak theory behaves in many ways like a superconductor and so does the vacuum of Chromodynamics, though in a different way. The Electroweak theory and Chromodynamics represent together our present understanding of the dynamics at the level of the fundamental particles. They globally constitute what is called the "Standard Model".The vacuum is defined as the lowest energy state of a system and has to be handled that way. Within our description of the dynamics it has a structure for which we find analogies in condensed matter physics.

From one problem to an other

Pauli, in his 1945 Nobel lecture based on the exclusion principle, presented again the theory which Dirac had described earlier in his own Nobel lecture, explaining how Dirac could eliminate the problem of negative energies using the exclusion principle.

In his lecture Pauli describes Dirac theory where in the actual vacuum all the states of negative energy should be occupied and only deviations of this state of smallest energy, namely holes in the sea of these occupied states are assumed to be observable and shows how it is the exclusion principle which guarantees the stability of the vacuum, in which all states of negative energy are occupied. He goes on explaining that the infinite "zero charge" of the occupied states of negative energy is then formally analogous to the zero-point energy of the quantized one-valued fields,

concluding that the former has no physical reality either and is not the source of an electromagnetic field.

Yet, at the end of his lecture, Pauli expresses his dissatisfaction and , following his own words, his "critical opinion that a correct theory should neither lead to infinite zero-point energies nor to infinite zero charges, nor should it invent a "hypothetical world" which is only a mathematical fiction before it is able to formulate the correct interpretation of the actual world of physics".

He then sets the goal very high saying that "A theory should be established which will determine the value of the fine structure constant and will thus explain the atomistic nature of electricity".

At present, the standard formulation of Quantum ElectroDynamics brings back the vacuum to its state of expected emptiness while exhibiting perfect symmetry between matter and antimatter. Yet, it leaves the fine structure constant as a parameter.

I can but try to put in a nutshell the new features brought by the quantum field theory approach.

In quantum field theory the field which describes an electron is no longer a simple wave function but an operator which destroys and creates particles. It can excite and de-excite the states on which it acts. The "negative" energies appear now as mere de-excitation energies and there is no longer anything puzzling about their appearance. The Dirac field destroys an electron and creates "something", a particle of a new kind . Its adjoint creates that electron and destroys the same "something". The definition of a charge operator from the field and its adjoint, which, by definition, cannot change the charge, together with the more technical imposition of causality, shows that the "something" must be a particle with the opposite charge and the same mass as the electron.

The quantum field approach has to give up the description of the electron as a single particle but it implies that one cannot describe the electron without describing also the positron. Matter and antimatter appear together and on the same footing while one deals only with the positive energy excitations of the most simple vacuum. The vacuum is back to emptyness. It contains neither electrons nor positrons.

Causality requires that the amplitude for emission of a particle is equal to the amplitude for the destruction of an antiparticle and vice versa. We call this crossing symmetry. Any process with an entering (emerging) particle is simply related to a process with an emerging (entering) antiparticle.This is illustrated by figure-1 with its either horizontal or vertical reading.

The consequences of hole theory can thus get more naturally expressed with a simple vacuum but the second quantized formalism is needed. This can be traced to the work of Majorana in 1937 but it took some time before the quantum field approach became part of the physicist's household.

The existence of antimatter, with this symmetry between matter and antimatter, is now seen as a direct consequence of the inner structure of quantum field theory. This is the formalism which combines relativity and quantum mechanics while requiring causality. The CPT symmetry of physics follows. Quantum electrodynamics turns out to be separately invariant under C (particle-antiparticle exchange), P (Parity) and T (Time reversal). Its formulation does not change when all particles are changed into antiparticles and vice versa. The system described may change but the equations which describe its dynamics remain the same!

Antimatter and causality

The reason for antiparticles was beautifully addressed by Feynman in his Dirac Memorial lecture of 1986 and one may at this stage look at a picture of Dirac and Feynman discussing physics (figure-3). Feynman illustrated his talk with clear and simple examples from which he extracted brilliant generalizations. He considered in particular the two successive scattering of an electron in an external field, showing that, if only positive energy states are allowed for the intermediate virtual electron which is propagating between the two scatterings, the second event cannot be limited to the light cone of the first one. As a result, if one event is in the future of the other, in a particular system, it may appear as happening before it in an other one. The consequence of relativity may then violate that of naive causality, with the intermediate virtual particle now running backward in time. The presence of antiparticles is necessary to restore a causal structure to the process seen with the opposite sequence of time. The event now seen as appearing earlier is understood as a pair formation producing the final electron and, together with it, a positron. The positron moves forward in time, as it should, to annihilate the initial electron at the time now seen as coming later. As Feynman puts it "the virtual particle of someone may be the virtual antiparticle of someone else". Antiparticles appear as needed to maintain an apparent causal structure whatever the reference frame in which one describes the event may be. At a more general level, one may say that antimatter is the way nature enforces causality in a relativistic and quantum world. This is encoded in quantum field theory.

Feynman in his original approach to quantum electrodynamics in the late forties had introduced this new view of antimatter, first brought up by Wheeler, where positrons appear as electrons running backward in time. The quantum and relativistic description of the evolution of an electron between two events has indeed to sum over many paths including those for which the proper time appears for a while to run backward. At that stage the electron appears as a positron. Positrons have to be there because such configurations are needed. Positrons have to exist as bona fide particles.

Feynman proposed several metaphors for the appearance of the positron. One of them is that of a bombardier in a plane which follows a road at low altitude and who suddenly sees the road becoming apparently three roads, but to realize, looking at things more widely, that this was only a switch back on the first road. This is illustrated by figure-4 which shows two versions of the same double scattering event. In the first case an electron "travels" between the two scatterings. In the second case pair formation is followed by annihilation with a positron and two electrons "travelling" in between. Including the positron is necessary to calculate amplitudes associated with the motion of electrons. Within a process, they look like electrons running backward in time. In Feynman's original conception, a vacuum filled with negative energy electrons was no longer needed to perform a calculation. Yet the expert knows that an important relative minus sign in his approach can be related to the exclusion principle in hole theory.

Theoretical physics as seen by Dirac

If the presence and the properties of antiparticles are now well understood, we can still reflect with admiration upon Dirac's achievement and try to benefit as much

Paul Dirac Richard Feynman

Figure 3: Dirac and Feynman discussing physics.

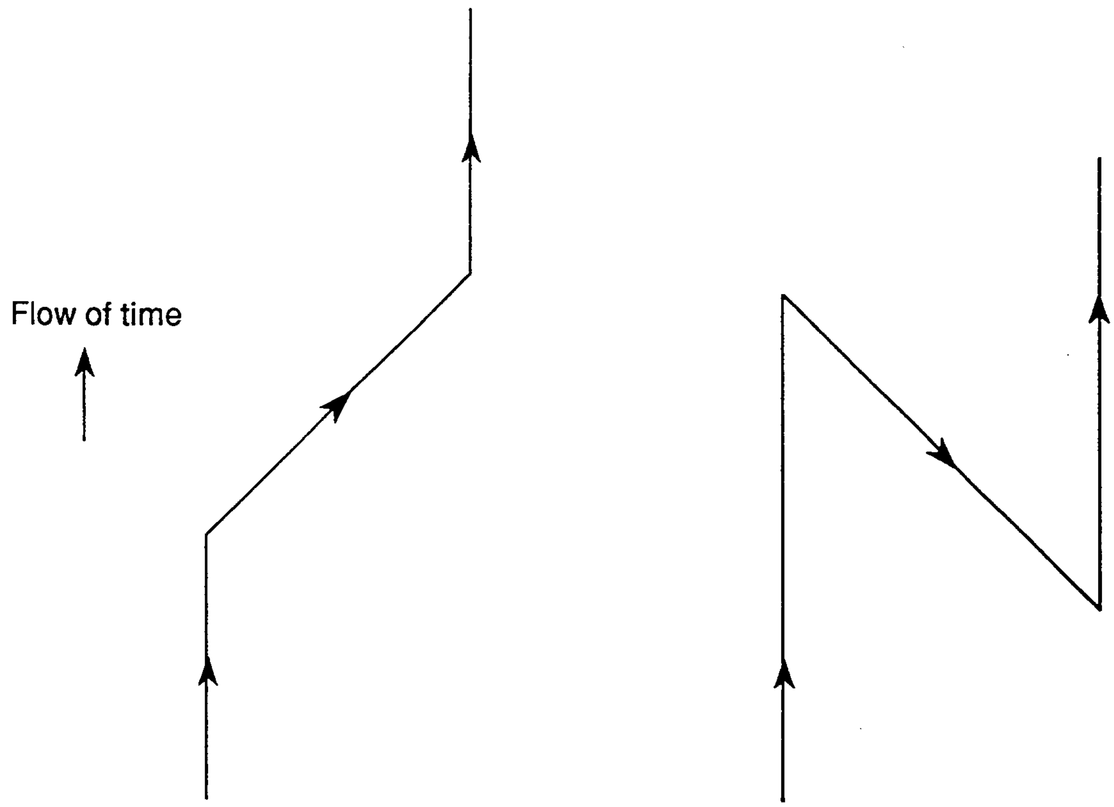


Figure 4: Double scattering in an external field seen in two different reference frames.
Left: Two scatterings
Right: Pair formation and annihilation

as possible from his masterful approach to physics. Didn't he arrived at antimatter because, as he said in his 1977 Varenna lectures: "One must be prepared to follow up the consequences of theory, and feel that one just has to accept the consequences no matter where they lead".

I would thus like to continue quoting from him as he describes the work of the theoretical physicists. This I shall borrow from the talk he gave during the ICTP Conference of 1968 organized by Abdus Salam on the theme "From a life of physics", in order to express at the time, as Salam had put it later "The sense of gratitude and adulation which everyone felt towards the great men of Physics still amongst us". I was fortunate to attend this conference. Let us read what Dirac said:

"I shall attempt to give you some idea of how a theoretical physicist works - how he sets about trying to get a better understanding of the laws of nature.

One can distinguish between two main procedures for a theoretical physicist. One of them is to work from the experimental basis. For this, one must keep in close touch with the experimental physicists. One reads about all the results they obtain and tries to fit them into a comprehensive and satisfying scheme.

The other procedure is to work from the mathematical basis. One examines and criticizes the existing theory. One tries to pin-point the faults in it and then tries to remove them. The difficulty here is to remove the faults without destroying the very great successes of the existing theory.

There are the two general procedures, but of course the distinction between them is not hard-and-fast. There are all grades of procedure between the extremes".

He then continues saying:

"With the mathematical procedure there are two main methods that one may follow,(i) to remove inconsistencies and (ii) to unite theories that were previously disjoint".

Then he hints at one of his successful methods:

"I would like to mention that I found the best ideas usually came, not when one was actively striving for them, but when one was in a more relaxed state... I used to take long solitary walks on Sundays, during which I tended to review the current situation in a leisurely way. Such occasions often proved fruitful, even though,(or perhaps because,) the primary purpose of the walk was relaxation and not research".

This is in particular how he tried to reconcile Relativity and Quantum Mechanics facing the difficulties with what became known as the Klein-Gordon equation. As he said, "Tensors were inadequate and one had to get away from them, introducing two-valued quantities, now called spinors. Those people who were too familiar with tensors were not fitted to get away from them and think up something more general, and I was able to do so only because I was more attached to the general principles of quantum mechanics than to tensors".

He then comes to his electron theory and the appearance of antimatter, saying:

"The introduction of spinors provided a relativistic theory in agreement with the general principles of quantum mechanics, and also accounted for the spin of the electron, although this was not the original intention of the work. But then a new problem appeared, that of negative energies. The theory gives symmetry between positive and negative energies, while only positive energies occur in nature".

As we saw, solving this new problem brought up antimatter.

Indeed, as Dirac later said in the same talk:

"As frequently happens with the mathematical procedure in research, the solving of one difficulty leads to another. You may think that no real progress is then made, but this is not so, because the second difficulty was really there all the time, and was only brought into prominence by the removal of the first.

This was the case with the negative energy difficulty. All relativistic theories give symmetry between positive and negative energies, but previously this difficulty had been overshadowed by more crude imperfections in the theory.

The difficulty is removed by the assumption that in the vacuum all the negative energy states are filled. One is then lead to a theory of positrons together with electrons. Our knowledge is thereby advanced one stage, but again a new difficulty appears, this connected with the interaction between an electron and the electromagnetic field".

This is the difficulty met with divergences which was to always bother him. These divergences, or infinite quantities, are stumbling problems met in calculations going beyond the simplest processes.

The parameters of mass and charge associated with the electron in the formalism of electrodynamics are not yet quantities measured under ordinary conditions. A free electron is accompanied by an electromagnetic field which effectively alters the inertia of the system, and an electromagnetic field is accompanied by a current of electron-positron pairs which effectively alters the strength of the field and of all charges. Hence a process of renormalization must be carried out, in which the initial parameters are eliminated in favor of those with immediate physical significance.

Dirac recognized the power of renormalzation theory describing it as a permitted change of the starting equations. But he said:

"You may think that the work of the theoretical physicist is easy if he can make any starting assumptions he likes, but the difficulty arises because he needs the same starting assumptions for all applications of the theory. This very strongly restricts his freedom. Renormalization is permitted because it is a simple change which can be applied universally whenever one has charged particles interacting with the electromagnetic field. The present quantum electrodynamics does not conform to the high standard of mathematical beauty that one would expect for a fundamental physical theory, and leads one to suspect that a drastic alteration of basic ideas is still needed".

We have gone a long way since in the exploration of the structure of matter. Yet it is impressive to see how the basic entities used in electrodynamics have been essentially merely generalized as new particles and new interactions have been discovered and studied. Quarks behave as electrons. It is said that after attending a lecture by Gell-Mann on quarks, Dirac who had remained silent eventually told Gell-Mann "You know, I believe in quarks". "Wonderful", said Gell-Mann, overjoyed, "but what is your main reason ?". "This is because they have spin 1/2" was Dirac's answer.

We have so far discussed antimatter in connection with the description of spin 1/2 particles. In quantum field theory half integer and integer spin fields are however treated on a similar footing using respectively anti-commutation and commutation rules. To each particle, whether a fermion or a boson, we are lead to associate an antiparticle with the same mass (a consequence of CPT symmetry) and the opposite internal quantum numbers, those which are not related to kinemetical properties.

2. Antimatter and present particle physics

Bound states of particles and antiparticles

There is a usual feeling that matter and antimatter when brought together result in a violent explosion. Indeed, when considering protons and antiprotons, we have an energy per particle which is close to 200 times that available in an hydrogen bomb! Yet things are not always to be that violent. When chunks of matter and antimatter would start to annihilate in great amount, one would quickly have between the two a cushion of high pressure radiation which would slow down the process. The correct metaphor is that of droplets of water thrown on a hot stove. They run around a lot before evaporating, being protected from the intense heat by a cushion of vapor.

At present, when studying production and annihilation processes, we deal with antiparticles almost one by one. When meeting a particle, an antiparticle often makes a bound state with a decently long lifetime before annihilating. The system cascades down many levels before annihilation takes place. Positronium and muonium are examples which have been very extensively studied. Worth mentioning in connection with present day particle physics is charmonium, built with a charm-quark and its anti-charmed antiquark. The quark is here sufficiently heavy that one can follow the dynamics of the system in a non relativistic way predicting the energy levels in a potential which is coulombic at short distances and linear (confining) at larger ones. One can calculate the electromagnetic transition rates between the levels. This is the "Hydrogen atom problem" at the quark level, namely a problem complicated enough to teach us something and yet simple enough to be handled in all details. In the case of charmonium, the system is very tiny. Energy levels are separated by hundreds of MeV, not the mere eV's met with positronium but the physics is very similar. There is hyperfine splitting as in usual atomic physics. The annihilation process is not so very fast by particle physics standards and can even be neglected in the calculation of the energy levels. Figure-5 shows the spectrum of photon emission from charmonium and the energy levels of the system.

More generally all known mesons are seen as quark-antiquark systems and this has a great calculation value, as first shown by Dalitz. The quark and the antiquark may belong to different species. Changing the quark into its antiquark, and vice versa, we get the antiparticle of the meson.

Particle production

Trying to understand the deep structure of matter, we probe the structure and interactions of particles which may first appear as elementary by colliding them against each other with energy as high as we can get. Present usual collision energies (in the hundred of GeV range) are much greater than the mass energy of many known particles (the proton mass energy is of the order of 1 GeV). Nothing then forbids part of the incident kinetic energy to turn into mass energy and in general a high energy collision is associated with an abundant production of particles together with as many antiparticles. In the late forties, the energy of the Berkeley Bevatron had been chosen to make the production of proton-antiproton pairs possible and this is the way the antiproton was discovered.The appearance of antimatter has become

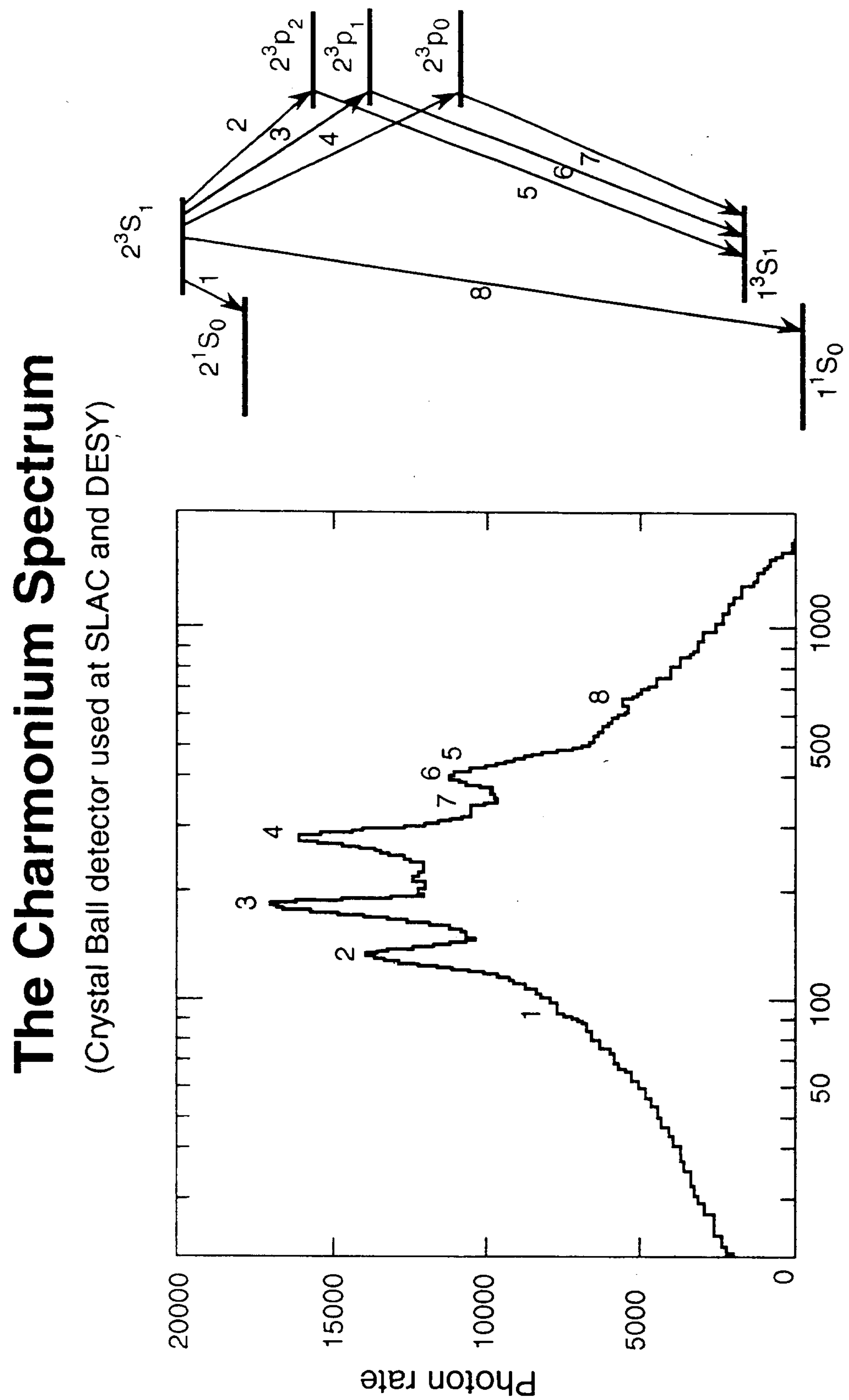


Figure 5: The spectrum of charmonium and the energy levels of the systems formed by a charmed quark and its antiquark.

bread and butter in the high energy collisions of present day particle physics. But it is not only its appearance which has become prominent, it is also its use!

Most of the produced particles and antiparticles are unstable but some of them are stable. In the vacuum, a positron is as stable as an electron and an antiproton is as stable as a proton. This is implied by CPT symmetry. One can then consider producing beams of positron or beams of antiprotons, which can then be stirred and accelerated in an accelerator as it is the case for beams of electrons or beams of protons. A very good accelerator beam puts together hundreds of billions time less particles than the Avogadro number which gives us the order of magnitude for the number of particles in a gram of matter. Even though antiparticles are hard to get , we can now easily collect enough antiparticles from high energy collisions to make decent beams.

Particle-antiparticle colliders

Having a beam of antiparticles has an important advantage. A beam of positron can be fed into an accelerator together with a beam of electron. The machine can keep the two beams circulating in opposite directions and accelerate them at the same time in the same vacuum pipe. One can thus transform a particle accelerator into a particle-antiparticle collider. This has been an extremely important development in particle physics.

First came electron-positron colliders. Positrons are indeed easy to get in great numbers. Electrons and positrons bunches are accelerated and, as they cruise in opposite directions in the machine, they come into collision in certain areas where they can mutually annihilate, their full energy being available for a wide array of processes. The collision energy partly turns into matter and antimatter energy and more and more particles can be produced in a single collision as the energy increases.It started with ADONE,at Frascati in Italy. Later, the great crop of data and results obtained at SPEAR, at SLAC, the Stanford Linear Accelerator Centre in California,with the discovery of charm and of the tau lepton at a collision energy not much in excess of 4 GeV, has been at the origin of a brilliant series of circular machines with increasing energy. They are CESR at Cornell, PETRA at DESY, the German laboratory in Hamburg, PEP at SLAC, TRISTAN at KEK, the Japanese laboratory near Tokyo, culminating with LEP at CERN , the European centre in Geneva. Figure-6 shows the location of the LEP ring which is about 100 meters underground, on the CERN site. LEP, with its present total collision energy of 100 GeV, now soon to be doubled, is the ideal machine to test in detail the consequences of the Electroweak theory. Electroweak theory has so far come out of all tests with flying colors. So did Chromodynamics which can also be submitted to many tests at these collision energies.

A circular machine has a great advantage. Bunches cross many many times since they coast at almost the speed of light and one can collect many events even if the probability to get one event in a bunch-bunch collision is very small. A particle bunch represents indeed an already good vacuum!

However, LEP will be the largest circular machine ever built. With higher energies, the synchrotron radiation of the accelerated beams gives a practically insurmountable problem trying to feed back to the coasting particles the energy which they radiate on every turn. On the other hand, linear colliders, whereby bunches of electrons and positrons are accelerated on two separate straight lines do

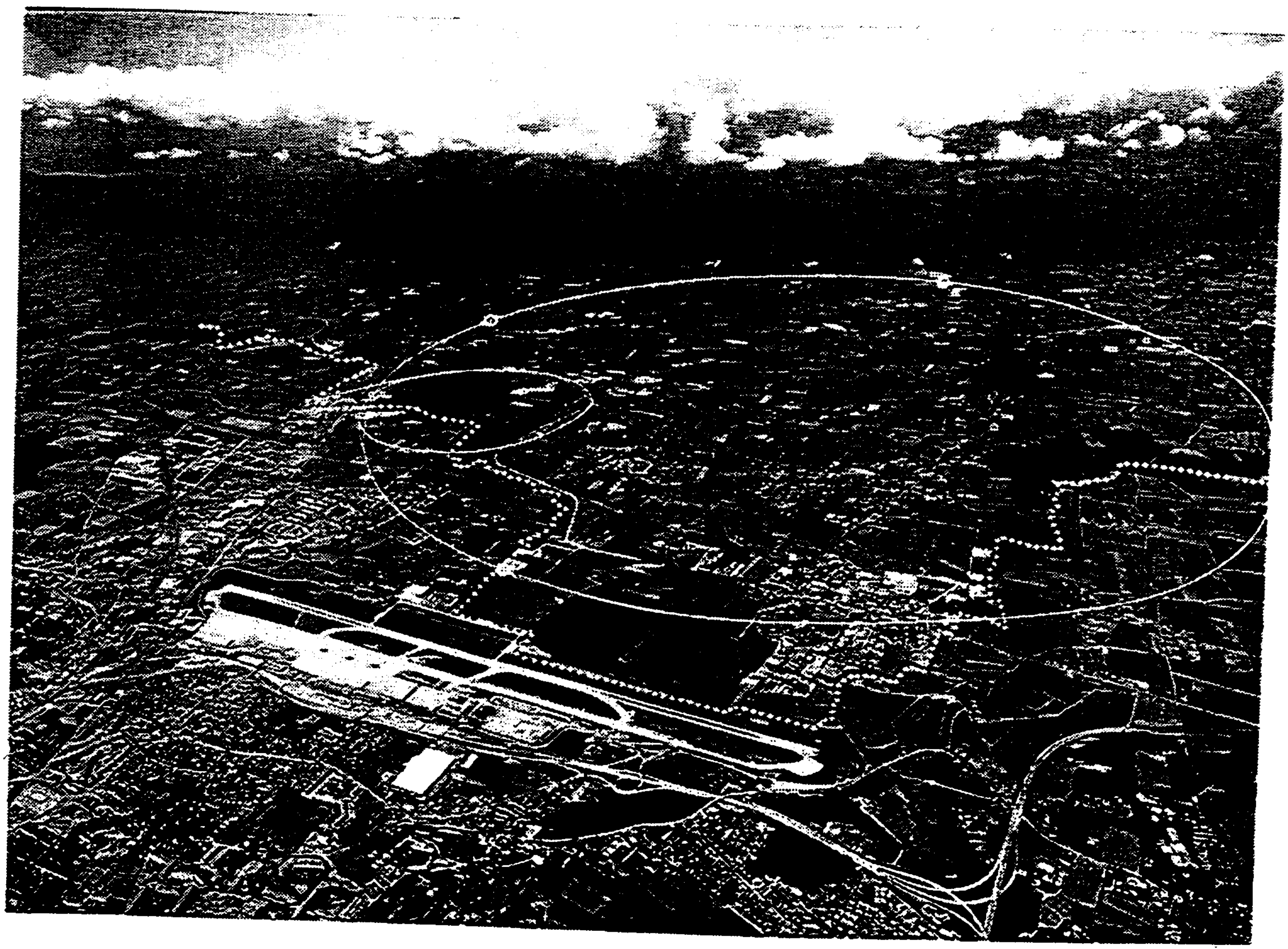


Figure 6: The LEP ring at CERN. The machine is in a tunnel about 100 metres underground. It collides electrons and positrons accelerated in opposite directions in the same vacuum pipe. Also seen (to the left) is the smaller ring of the SPS which became the first proton-antiproton collider.

not give this problem. They should be the answer but the accelerated bunches now collide only once and they have to be made enormously small to enhance the probability of collisions between particles. At present very high energy linear colliders are considered in many laboratories drawing board, with pieces on test benches. This should eventually be the way to extend electron-positron collisions to much larger energies, and one of them, the SLC at SLAC, already works at 100 GeV of collision energy.In this ingenious device,electrons and positrons are separately accelerated in the same machine and brought into head on collision after bending through two separate arcs.

Antiprotons are harder to get since a proton-antiproton pair is about 2000 times more massive than an electron-positron pair. One needs a very high energy collision to have a decent chance to produce one. They have to be preciously collected and stored before a decent beam can be obtained. However, because of the heavy mass there is now no problem with synchrotron radiation. One can accelerate antiprotons to very high energy in a circular machine together with protons circulating in the opposite direction.

CERN, with the talent and drive of Carlo Rubbia and Simon van der Meer, was the pioneer in that field. Antiprotons could be collected, stored and cooled into a good beam, in a dedicated machine, and then accelerated together with protons in the SPS. Figure -7 shows the CERN antiproton accumulator where antiprotons are captured ,cooled and accunulated. One can see the wave guides set across the machine. They transmit in a straight line signals associated with particles straying away too much from the mean energy so that this can be corrected after they have travelled along the corresponding arc at almost the speed of light. Antiprotons thus stacked and cooled to a circling beam of well define energy are fed into the PS, accelerated and transfered to the SPS where they are further accelerated together with a beam of proton circling in the opposite direction. Collision energy of 600 GeV could be achieved between protons and antiprotons. This was necessary to produce the W and Z which were thus discovered, in 1983. The W and the Z are the carriers of the weak force in the Electroweak theory. For instance, in neutron ß decay, the neutron emits a (virtual) W as it transforms itself into a proton. The W fragments into an electron and an antineutrino. The mass energy of the W is about 80 times that of the proton. In ß decay, it can appear only as a quantum fluctuation of very short time duration. With enough collision energy it can emerge as a bona fide particle. The same applies to the Z which has a mass energy of about 90 times that of the proton.

Proton (and antiprotons) are complicated objects. They contain quarks, antiquarks and gluons which all take part in the collisions. One may say that they correspond to broad band beams of quarks, antiquarks and gluons. As the energy increases, proton-antiproton and proton-proton collisions look more and more alike. The simple annihilation process of the colliding particles, so important in electron-positron encounters with its simple one photon process, looses its special prominence. What matters primarily is thus to reach very high energies while using a single accelerator already built to accelerate protons. The CERN proton-antiproton mode of operation has been a great success in the eighties. It has now been phased out. At present, Fermilab has a proton-antiproton collider of a much higher energy of 2000 GeV. This large energy was needed for the discovery of the very massive top quark, which is produced in pairs top-antitop (a mass energy of the order of 350 GeV).

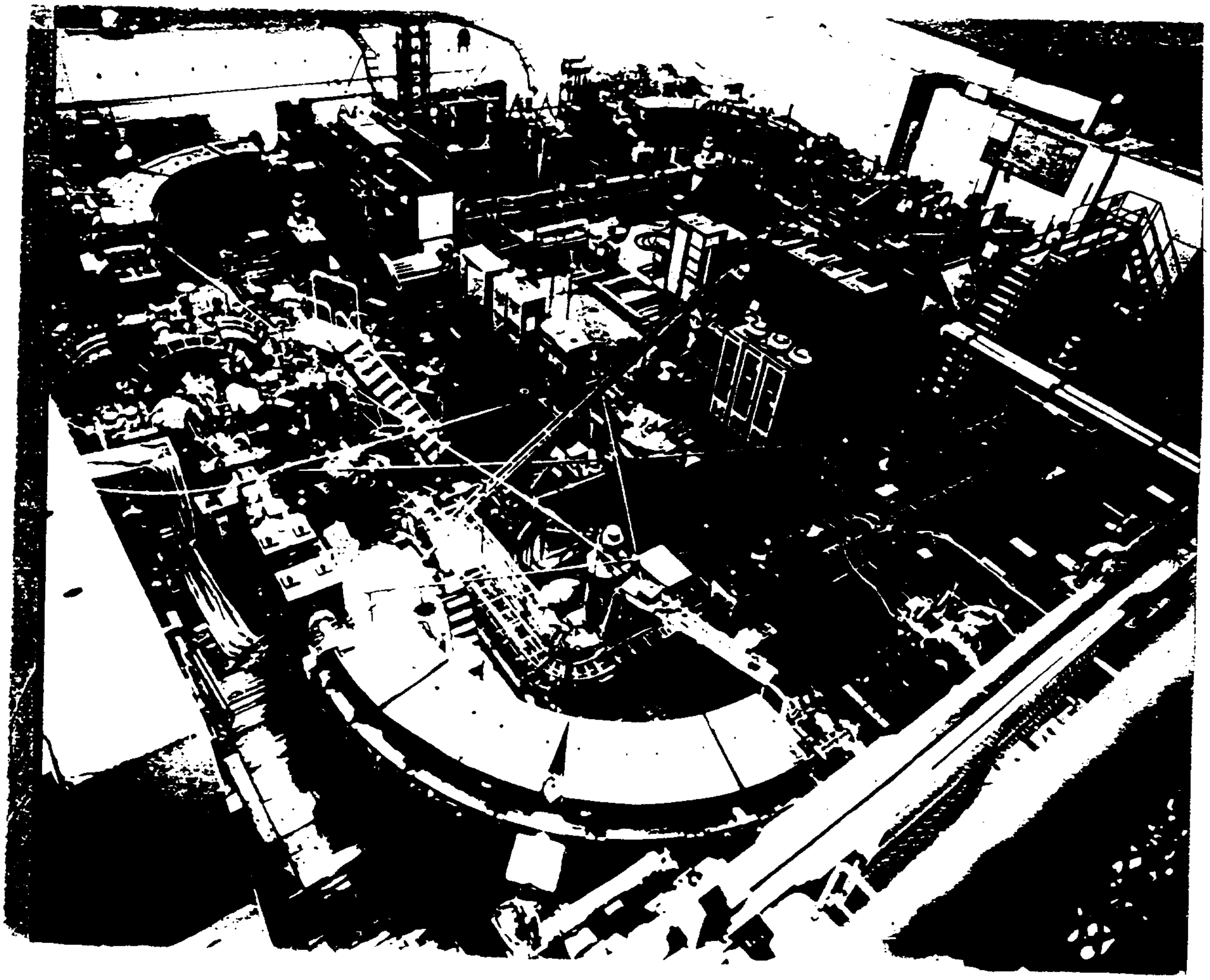


Figure 7: The CERN antiproton accumulator. One sees the lines set across the machine which transmit information about the beam as it circles around and control the cooling devices.

Whereas one now produces intense beams of antiprotons, they are typically two to three orders of magnitude less dense compared to what one can do with protons. Since the luminosity of the machine, which controls the reaction rate, is also a very important parameter when searching for rare but most interesting processes, the new CERN collider, the LHC, with 14,000 GeV of collision energy, will be a proton-proton collider. One needs two separate beam pipes and magnetic structures but this is the accepted price to pay for luminosity.

One may illustrate the power of a proton-antiproton collider with two examples. One of them (figure-8) is the production of a Z in quark-antiquark annihilation, with its subsequent decay into an electron-positron pair. This is the way the Z was discovered in 1983. The other one (figure-9) is the production of two hadronic jets as point like constituents within the colliding proton and antiproton (quark, antiquark or gluon) individually collide to give two particles shot at wide angle and which eventually appear as jets of hadrons. This is the modern aspect of the Rutherford experiment, giving evidence for hard point-like scatterers within the colliding particles.

The scattered constituents are "colored" . In Chromodynmics the "color" of a quark takes the role of the charge in Electrodynamics. The scattered constituents cannot escape into the vacuum which is opaque to color. The penetration energy is of the order of 1 GeV/fermi and they thus don't go very far before part of their energy turns into light hadrons and antihadrons, mainly π mesons, which emerge as a jet replacing the original particle. We do not see quarks and antiquarks but we see jets which are almost as spectacular.

Dealing with antimatter

With electron-positron colliders and proton-antiproton colliders, available antimatter has quickly become a very important tool in particle physics. There is however not only the high energy frontier. Worth studying are also specific features associated with the annihilation of proton and antiprotons at low energy, whereby a relatively large amount of mass energy turns into particles and antiparticles allowing a detailed study of the spectroscopy of the objects formed. At CERN, the stored and cooled antiprotons can also be decelerated and stored in a dedicated machine, LEAR, the Low Energy Antiproton Ring . The machine is shown in figure-10 where one also sees its feeding beam line. LEAR provides an intense source of antiprotons which can be extracted at will. They are no longer a minority among many particles as when produced in proton-proton collisions. In vacuum they live forever and LEAR can keep a trillion antiprotons for days.This allows many scattering and annihilation studies, looking in particular for the properties of the many types of particles which are produced .

There are many other exciting things which one can do with an intense source of slow antiprotons. They can be captured in atoms where they replace an electron and orbit with specific atomic levels. One can study the spectroscopy of such compact antiprotonic atoms. Worth a special mention are the CERN recent results on antiproton helium atoms. One can also capture very low energy antiprotons in a trap. The present practical realization is offered by the trap invented by Hans Dehmelt. In the present Penning trap, the kinetic energy can be brought down to a thousand of an eV through collisions with electrons and the antiprotons can be held trapped in a magnetic field circling in a small "bottle" for months. Figure-11 gives a schematic

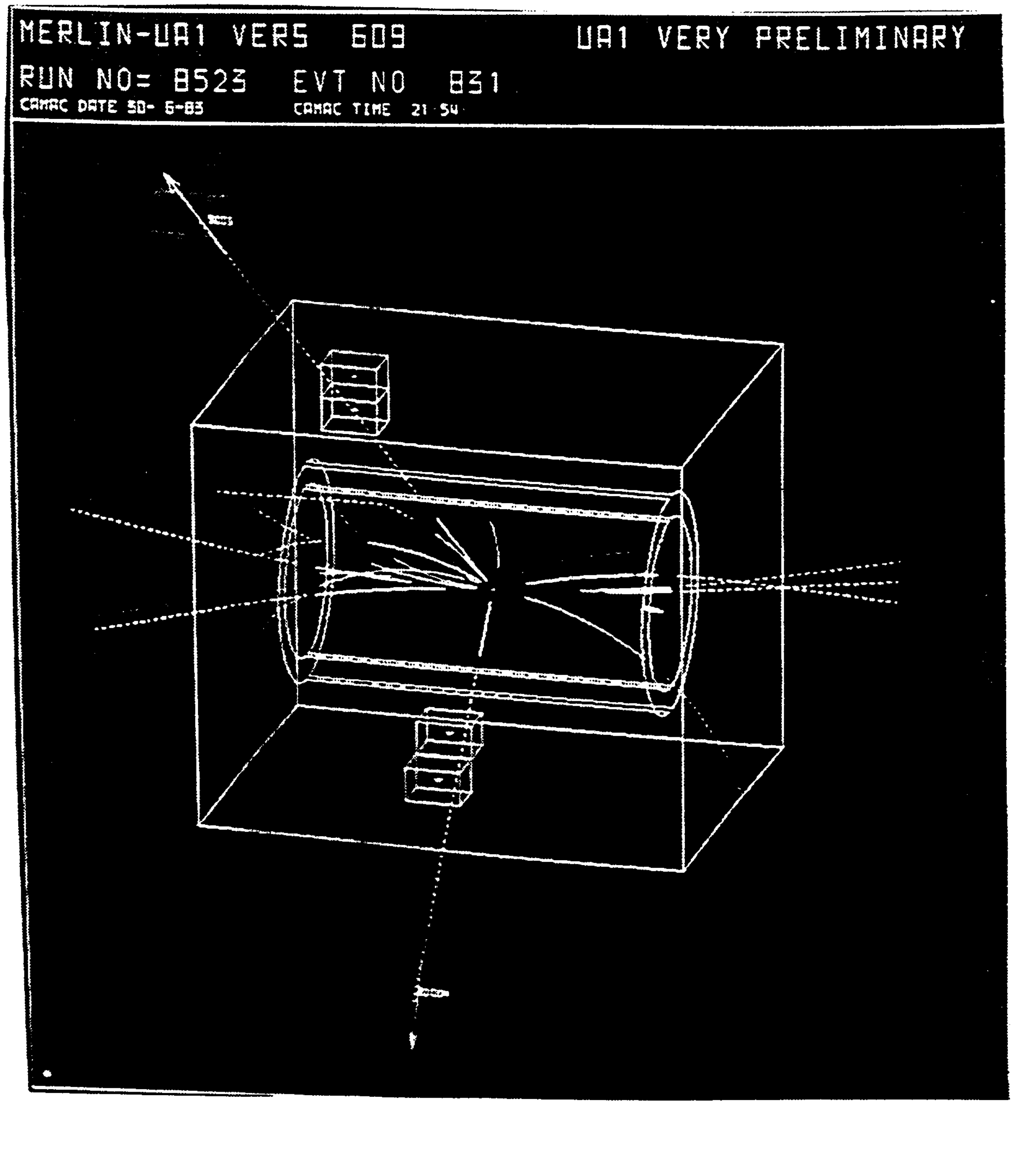


Figure 8: Production of a Z particle during a proton-antiproton collision (UA1 detector). The Z decays into an electron-positron pair which provides a clear signature.

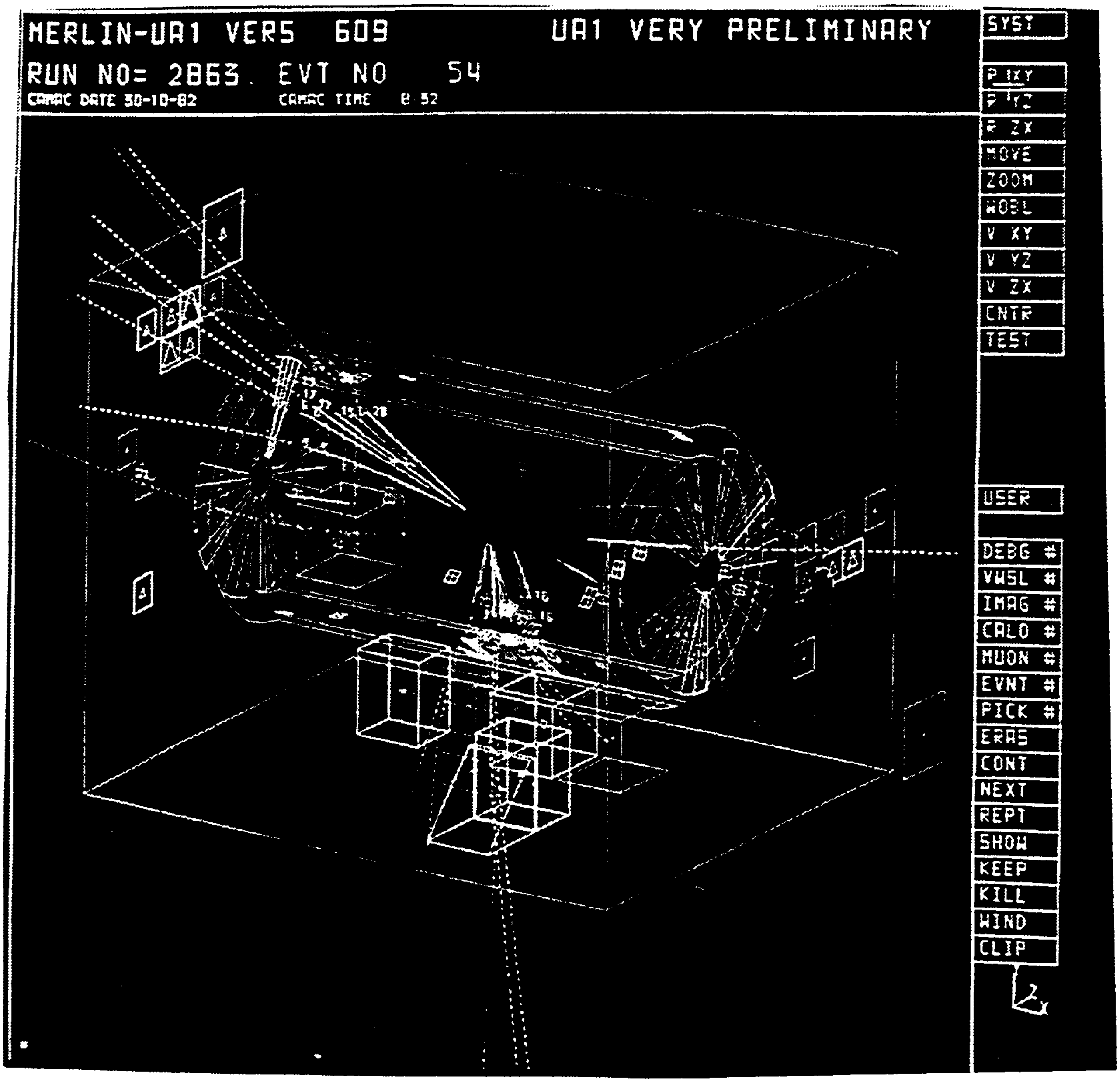


Figure 9: Production of two hadronic jets during a proton-antiproton collision (UA1 detector). This is the modern form of the Rutherford experiment whereby point-like constituents within the colliding particle hit each other head on and recoil at a wide angle.

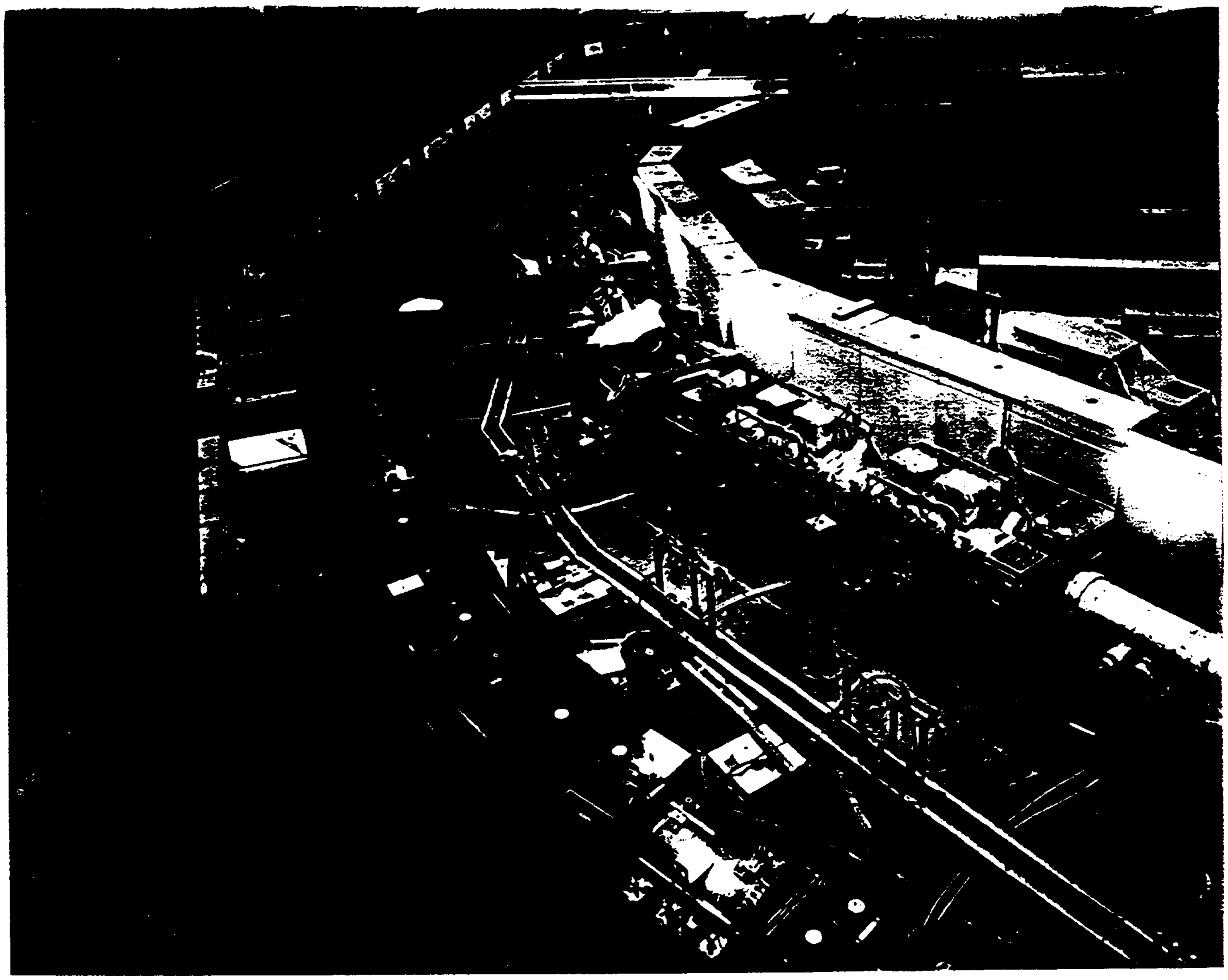


Figure 10: LEAR - The low-energy antiproton ring, which stores a large quantity of antiprotons decelerated to low energies. They are held circling in a magnet ring and extracted for experiments.

drawing of a Penning trap in use at CERN. It is 13 cm long. Within the trap, one can compare the motion of antiprotons in a magnetic field to that of protons. This is the best ever test of the expected identity between the proton and antiproton mass. The precision achieved is at the level of 10^{-9}. An other LEAR experiment is attempting to compare the gravitational pull on protons and antiprotons.

The next step would be to make real "full" antimatter, making antihydrogen atoms from antiprotons and positrons. An antiproton would capture a positron created together with an electron in its collision with a heavy nucleus. Whereas this may provide evidence for antihydrogen, reaching decently large quantities would require combination between antiprotons and positrons stored in traps. This now seems possible but still looks as a few years away with present techniques. The practicle interest of making antihydogen is to eventually reach high densities, those of a solid and not of a plasma.

We can do very exciting physics with tiny quantities of antiparticles, and in particular build accelerator beams. We would need a thousand billions accelerator bunches of antiprotons to reach one gram. The present price tag for antiprotons has been estimated at about 10^{16} pounds per gram. Yet, as we shall see, antiprotons, even in relatively small numbers, have already found some uses outside of particle physics, and many more may be to come.

Particle-antiparticle oscillations

A very special study of antimatter in high energy physics is worth singling out. It is the analysis of the neutral K system, soon to be followed now by the analysis of the neutral B system, where Beauty replaces Strangeness (or is associated with Strangeness) in the meson structure. Strangeness and Beauty are two among the internal quantum numbers often referred to, which turn into their opposite when going from a particle to its antiparticle.

We saw how mesons are built of a quark and an antiquark. The neutral K meson is built out of a d-quark (charge -1/3) and a strange antiquark, which has antistrangeness (and charge +1/3). It is globally neutral but different from its antiparticle which is built out of an anti d- quark and a strange quark. It has the opposite strangeness. Strangeness is conserved in the production process which involves other final particles so that, depending on the event considered, one knows that either a K-meson or an anti K-meson has been produced. The meson flies off. Its decay is indeed mediated by the weak interaction, which violates strangeness conservation and "takes some appreciable time" to act. As the meson flies the weak interaction can also eliminate the strangeness from a quark which is transformed into a quark without strangeness . At the same time, it can put antistrangeness on an antiquark which did not have it in the first place. As a result a neutral K meson is turned into its antiparticle (the antiK meson) or vice versa. The two eigenstates of the mass matrix, which correspond to a specific evolution of the wave function with time (damped by decay at a particular rate) will therefore be mixtures of the K and anti K states. The probability of seeing the particle either as a K meson, or as an anti K meson oscillates with time according to the (tiny) mass difference between the two eigenstates of the mass matrix. The particle and the antiparticle continuously exchange their role.

Things are particularly simple in the neutral K meson case since the two eigenstates of the mass matrix have very different life times. One of them quickly

disappears while the other one remains about a thousand times longer. The first one is almost an eigenstate of CP with value +1 and a favored decay into two π mesons. The second one is almost the CP eigenstate with value -1 for which the easy two π mode is forbidden. Not quite though, and the small admixtures between the two CP eigenstates shows that CP invariance is violated in neutral K decay. This came as a big surprise in 1964. This is still a puzzle today and the experimental appearance of the violation of CP invariance is still limited to neutral K decay. It is possible that this could however be a natural feature in the Standard Model with 6 quark species, that is something which has no specific reason not to appear. It is therefore extremely tempting to collect similar evidence in other cases. The study of neutral B decay, where a b-quark is associated with either an anti d-quark or an anti strange quark (and the other way around for the anti B meson) looks particularly promising in the Standard Model. What we said about the neutral K system, with its oscillation between particle and antiparticle also holds for each of the neutral B-systems. However things are experimentally more complicated since the two eigenstates of the mass matrix now correspond to practically identical decay rates and remain on the same footing as the meson flies off and eventually decays. One can give special attention to decay modes which are CP eigenstates but they are now rather rare. Nevertheless, granting enough properly tagged B (and anti B) mesons, the detailed study of the evolution with time should be possible. Here, however, comes the next problem. The B meson being rather heavy it is hard to produce and it is difficult to collect big enough a sample. This has motivated the construction of a dedicated b-factory at SLAC at Stanford and also at KEK in Japan, the construction of a special detector at HERA at DESY and it has been at the origin of a special proposal for the LHC. We may hope that the detailed study of neutral B-decay will soon bring a new and valuable light to CP violation.

In any case CP violation is there and this could be at the origin of the excess of matter over antimatter in the early universe. In the explosive condition of the Big Bang, CPT symmetry could not restore an asymmetry between matter and antimatter brought by CP violation, as emphasized long ago by Zakharov.

3. Antimatter at the cosmic scale

Physics present a beautiful symmetry between matter and antimatter and what could be more natural than a universe where matter and antimatter would be both equally present, even if, in our surroundings, we have to happily acknowledge that matter is overwhelming. However, probing the Cosmos we see no sign of the expected effects associated with a large amount of matter coming into contact with a large amount of antimatter with a large amount of radiation of specific signature. This even holds up to the super cluster level, which is at present the ultimate grouping scale. It seems that all the universe which we can see is made of matter. This actually tally with our view of the universe originating from a Big-Bang with densities and temperatures which are the largest, the closest one tries to get to the beginning, extrapolating back in time from our present information. At the beginning of the universe the temperature falls as the inverse square root of its age. The density falls as the inverse square of its age. The physics which takes place is the one which we explore with particle physics. With the energy at LEP (100 GeV) we have the collision conditions which prevailed when the universe was 10^{-10} s. old.

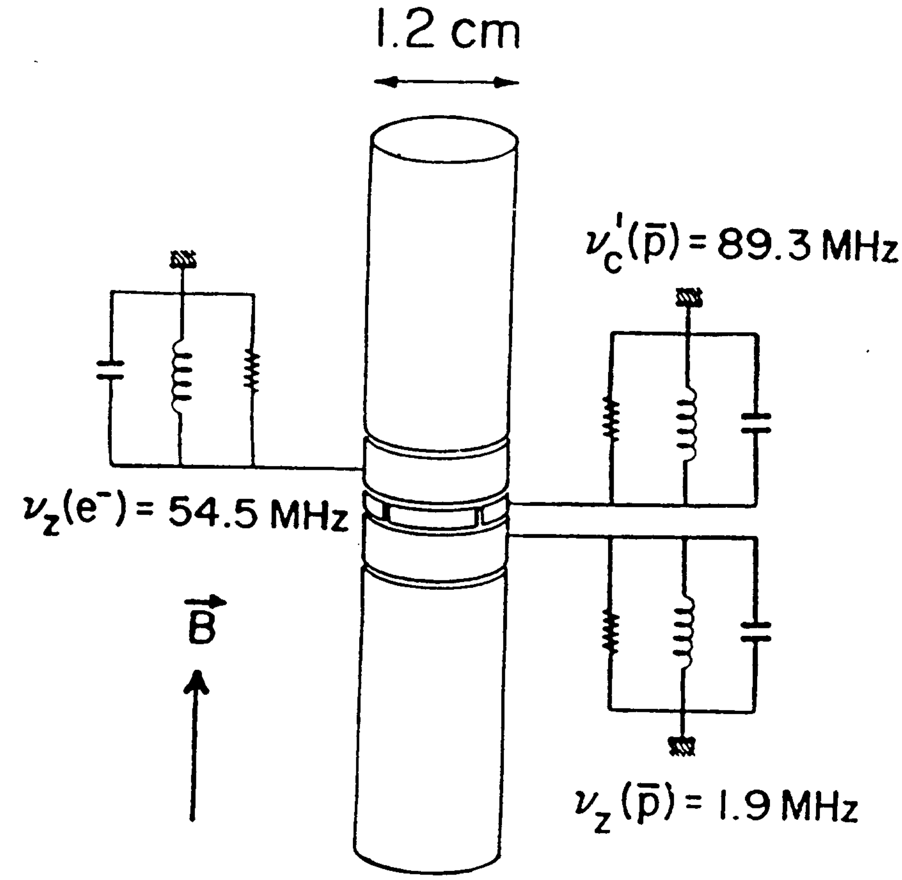


Figure 11: A schematic drawing of the Penning trap used in the LEAR experiment
(page 12) PS 196. In the trap, 13 cm long, antiprotons are cooled via repeated collisions with electrons. Antiprotons with energy 10 billion times lower than those in LEAR can be stored and studied over long periods of time (months), in a small apparatus.

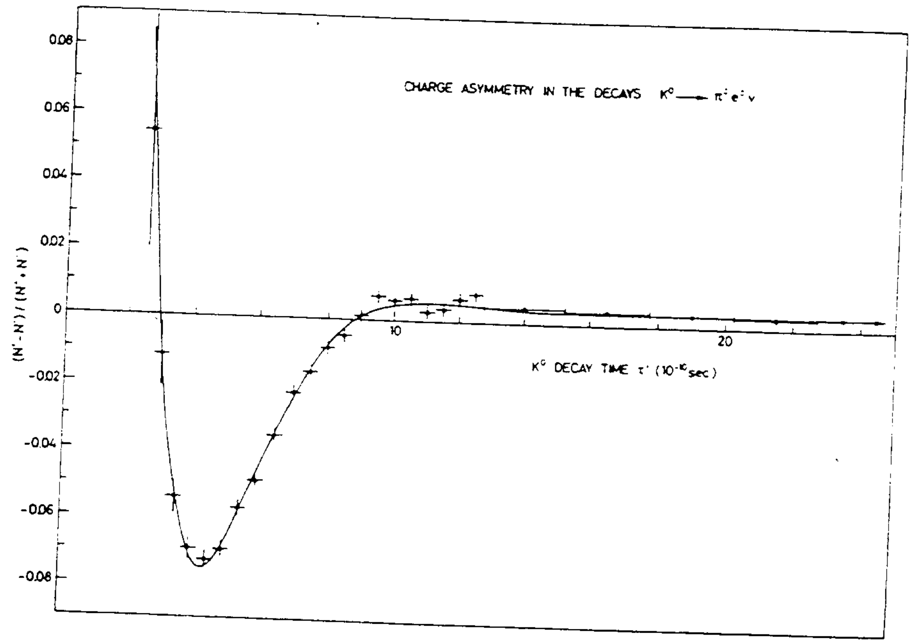


Figure 12: Oscillation between a neutral K meson and its antiparticle. This is seen through the appearance of either an electron or a positron among the decay particles in the electron (positron), pion antineutrino (neutrino) mode. The K^0 gives only a positron whereas the anti K^0 gives only an electron. The observed electron positron charged asymmetry as a function of time follows the oscillation between the K meson and its antiparticle. The left over asymmetry at longer times bears witness to the violation of CP symmetry. This decay mode can thus be used to define through the description of an experimental result what we call a particle (the electron) as opposed to its antiparticle (the positron).

The universe looks very quiet when observed with visible light. But, when looked at through radio waves or X-rays and gamma rays, it is rich in violent events in which antimatter (in any case positrons) comes readily into the picture.

Two events during the Big-Bang

I shall here limit myself singling out two periods in the early universe for which matter-antimatter symmetry is particularly relevant. They are selected for their being very important and of different kind.

The first period was when the universe was about 1 second old. This is the time when the temperature fell below 1 MeV. Up to that time electrons and positrons were continuously annihilating into two photons but two photon collisions could produce at an equal rate electron and positon pairs. There was therefore an equilibrium between electrons, positrons and photons, which were practically equally numerous in the universe. When the temperature fell below 1 MeV, as the universe was expanding and cooling, electrons and positrons could still annihilate into photons but the photons soon did not have enough energy to make electron-positron pairs. The massacre of electrons and positrons was no longer compensated by a continuous production process. All positrons annihilated against electrons. There remained only one electron survivor in a billion. Photons became by far the more numerous particles in the universe. This was the end of the so called lepton era when electrons and positrons dominated.

The second period was when the universe was about ten microseconds old,when temperature was about 200 MeV. In the framework of Quantum Chromodynamics we expect that, at such a temperature, the vacuum becomes no longer transparent to the "color" of the quarks. Up to that time the universe was a plasma of quarks, antiquarks and gluons which were freely roaming and crashing into each other. When the universe became opaque to color, quarks and antiquarks had to bind into globally colorless hadrons (protons, antiprotons and π mesons for instance) since only such particles could exist in the new vacuum. But the rest mass energy of the protons and antiprotons (about 1 GeV) which were created was already much larger than the surrounding temperature (200 MeV). Protons and antiprotons quickly annihilated against each other since the density was very high and they could not be formed again in pairs, through the collisions of the surrounding particles. There was therefore a massacre of protons and antiprotons. All antiprotons disappeared against protons leaving only one proton in a billion as the survivors. This was the end of the quark era during which quarks and antiquarks had been the most abundant particles in the universe.

One may then wonder why the number of surviving protons appears to be equal to that of the surviving electrons, both being a billion times less than the photons in the cosmic radiation background. Attempting to answer this question would lead us to CP violation in a Grand Unified Theory . Whereas the symmetry present in such a theory could have prevailed in the very early universe, its eventual breaking as the universe cooled down would have produced a differentiation between quarks and leptons appearing separately but with the proper relative numbers. This corresponds, however, to an energy domain where theoretical ideas are not yet supported by experimental information.

In the very early universe matter and antimatter were almost on the same footing. This is certain from the overwhelming abundance of photons over protons

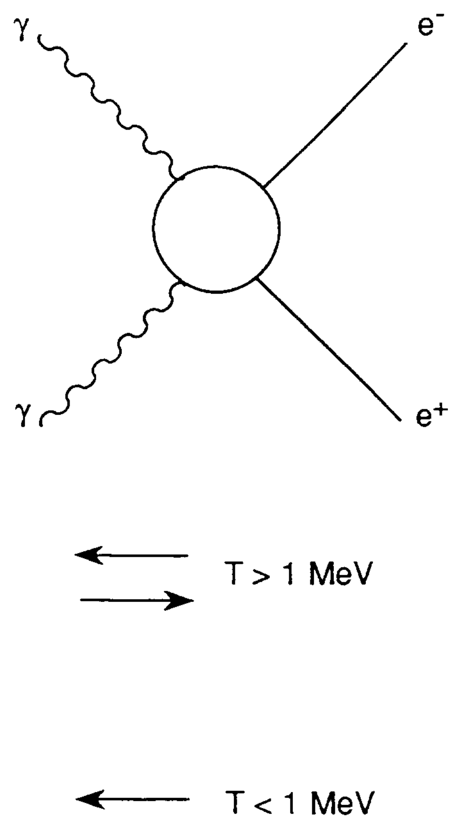


Figure 13: Electron positron annihilation into two photons and pair formation in photon-photon collisions.

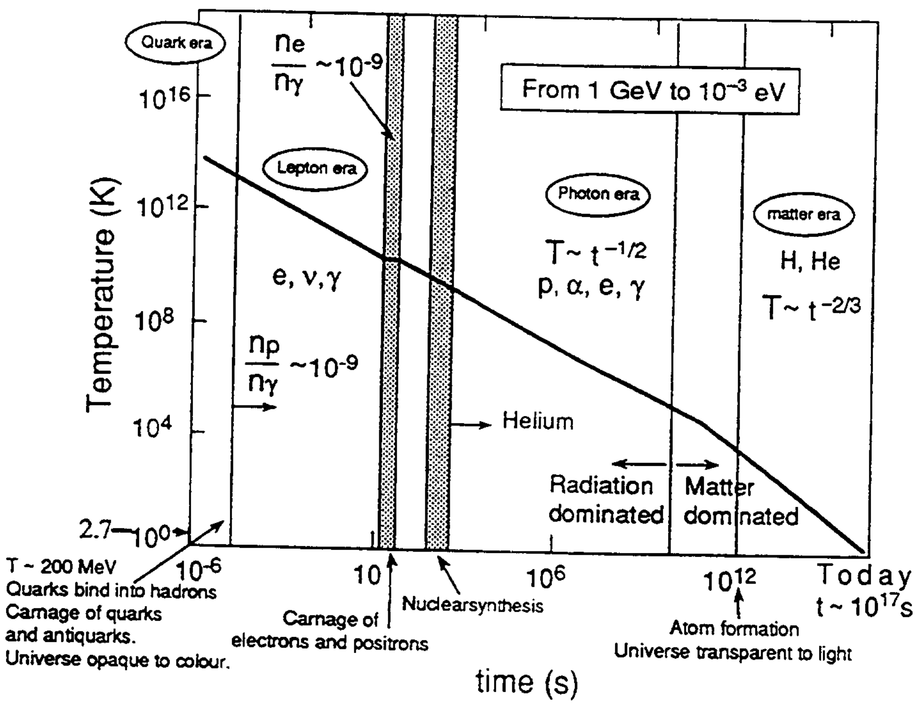


Figure 14: A piece of the thermal history of the Universe showing in particular the two events which occurred when the temperature went through 200 MeV (carnage of quarks and antiquarks) and 1 MeV (carnage of electrons and positrons) respectively.

and electrons in our present universe. Antimatter is likely to have fully disappeared from the cosmic scene, through the two successive massacres which we described. This is the prevailing view. It seems that there is no sign of large quantities of antimatter up to the super cluster level which is the largest type of structure known. Yet one can still entertain views in which antimatter could still prevail in some corners of the universe. This motivates searching for antinuclei in cosmic rays, something which requires a space experiment.

4. Other practical uses of antimatter

Next to the prominent use in making accelerator beams, other more practical applications are already worth noting. Positron beams are used in condensed matter and atomic physics but medical applications are worth a special description.

Positron Tomography

Positrons are easy to make and they have already been put to an efficient medical use. Positron Emission Tomography (PET) uses positrons which originate from neutron deficient radioactive nuclei. The annihilation of the positrons against electrons produces pairs of back to back gamma rays of a well defined energy which can be detected in coincidence for a rather precise localization of the emitter. The positron mean free path is of the order of 1mm. There are Positron emitters such as Carbon-11, Nitrogen-13, Oxygen-15 or Fluorine-18, which are easily made parts of biological substances used as tracers. The detection of their whereabouts inside the human body can be used not only to localize anomalies within specific organs but also to study biochemical changes as they take place. Pathological developments can thus be spotted out long before any anatomical changes are detectable. The most commonly used radioactive isotopes, as those mentioned, have mean lives which corresponds to typically 10 minutes. They have therefore to be made on the spot. This is done with dedicated cyclotrons which are now available as compact user friendly tools. The PET camera detecting the gamma rays provides an in vivo measurement of the localization of the tracer as a function of time. One gains over the long (and still much) used isotope imaging, both in sensitivity and in spatial resolution.

The whole equipment is now available in a highly automated form, suitable for hospital use. The PET scanner assembled at CERN and operational at the Geneva's university hospital is shown in figure- 15.

At present there are already 140 PET centres in the world and their number is increasing at the level of close to 20 per year. There are many applications in the fields of oncology (tumor detection), neurology and cardiology. Clinical use is expected to grow rapidly.

Next to this beautiful medical use of positrons, one may now venture in the still speculative use of antiprotons.

The economics of antiprotons

We have seen how they can be produced in high energy collisions, collected and stored. Things are still not very efficient. The produced antiprotons are often lost

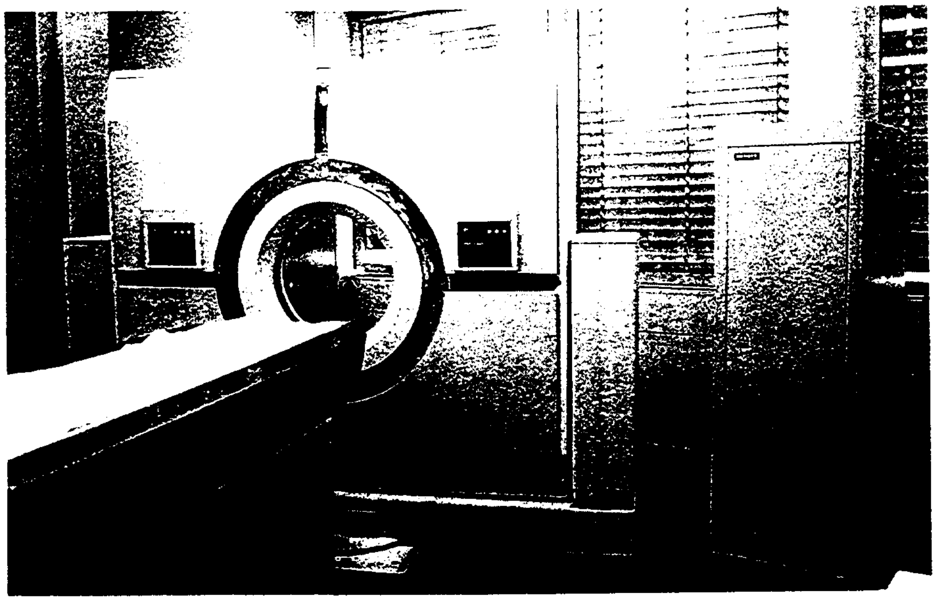
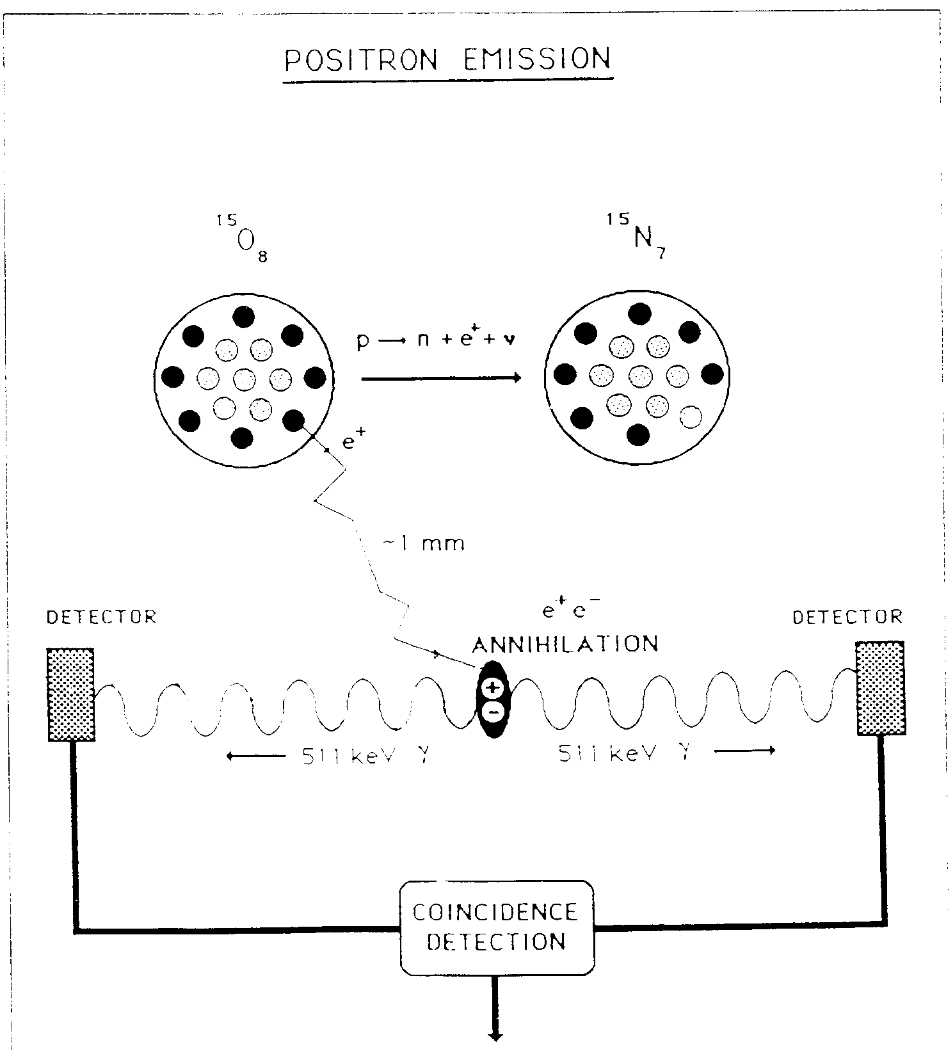


Figure 15: Positron emission tomography. the PET scanner assembled at CERN and operational at Geneva's University Hospital. Hundreds of patients have been scanned with this equipment (upper Figure). The principle of the apparatus: the annihilation of a positron with an electron produces two 511 KeV back to back photons and detecting them measures the position of the event immediately.



when one tries to focus them with magnetic lenses and capture them in an accelerator ring. The best capture efficiency achieved so far is of the order of 1%. However, once antiprotons have been stored and cooled, being all brought into a beam of well defined low energy, handling them from one machine to an other is already possible with 90% efficiency. Present antiproton "bottles" (figure-10) have been brought to hold 10^{12} antiprotons. This is still of the order of 10^{-12} grams only. The energy associated with their annihilation would only be of the order of a few hundreds Joule. The overall energy efficiency is therefore still of the order of one part in hundred million.

A small magnetic trap can, however, be used for holding such an amount of antiprotons. We already mentioned the Penning trap. It has been used to hold 10^5 antiprotons for months and holding the full load of 10^{12} appears possible. It is only a meter long and the antiprotons are circling in the vacuum, away from the walls, in the strong magnetic field produced by superconducting magnets.

Antihydrogen has still to be produced but, once it is the case, it could then also be stored despite its neutrality using its diamagnetic property. It could be stored in dense solid form as antihydrogen-ice. This works for hydrogen-ice.

At present, it seems that antiprotons could be used for tomography in much the same way as proton beams have been used instead of X-ray, following the pioneering work of G. Charpak. Detection systems for charged particles, such as wire chambers, can be made very efficient and the probing intensity can thus be brought to a very low level with a very limited radiation exposure of the patient. With proton tomography one has however to use relatively rare wide angle scattering events in order to locate with precision the target having been hit. The irradiation intensity has to be adjusted accordingly. But low angle scattering hits remain potentially harmful while providing little information. On the contrary, with antiprotons, each hit can be precisely located through an annihilation producing several particles independently detected . One can then much reduce the irradiation level. A good three-dimensional image of an organ could be obtained with a mere billion of antiprotons. The point where heavy particles come to rest and make the most damage can be relatively accurately defined and antiprotons, then used with higher density, could also be used at eliminating the tumors which they would allow one to detect. Efficient medical use could probably proceed with the tiny quantities presently available from high energy machines.

Looking in the more distant future one could be more speculative and consider rocket engines based on antimatter, but we are now talking about milligrams of antimatter (a billion times what is presently typically available) to hundred milligrams depending on the ambition of the flight. The annihilation of antimatter would be used at heating a radiator at very high temperatures (3000 K). The propellant fuel would be shot through the radiator and exhaust at high velocity. With such high temperatures and exhaust velocities, a spacecraft may work with a much smaller quantity of fuel (or fuel to payload ratio) than presently the case with chemical fueled rockets. With a few milligrams of antihydrogen one could heat several tones of propellant to such temperatures. Happily this interesting application for planet exploration would come with quantities thousands times short of what would be needed to get the equivalent of a nuclear bomb!

This may seem like science fiction but one should not underestimate engineering ingenuity when considering several decades ahead.

Tiny quantities of antimatter (a thousandth of a billionths of a gram) are already very much in use. One can wonder with awe at what could be achieved when only milligrams would be in use!

But, besides considering these practical applications, at present and in the future, we can but admire Dirac's great achievement at predicting the existence of antimatter. In the sixties, Heisenberg characterized the postulation of antimatter by Dirac "as the most decisive discovery in connection with the properties or the nature of elementary particles". The existence of antimatter is probably the revolutionary concept of physics in this century which had the strongest inpact on the general public.

This talk was presented during a symposium at the Royal Society honouring P. Dirac, on that day, a plaque was set in Westminster Abbey.