ELEMENTARY PARTICLE PHYSICS

SOME DECISIVE CONTRIBUTIONS BY GREEK SCIENTISTS

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Abstract

In the past 40 years the investigation of high energy phenomena has led to the discovery of a very large number of elementary particles. We now know that only a few of these - the quarks and the leptons, should be considered as elementary. We discuss three decisive contributions to elementary particle research involving Greek scientists: the principle of strong focusing first discovered by Nicholas Christofilos, the discovery of the antiproton in which Tom Ypsilantis participated, and the prediction of the existence of a fourth quark as put forward by Glashow, Iliopoulos and Maiani.

1. Introduction

Elementary Particle Physics, also referred to as High Energy Physics, is the field of study of the properties and interactions of the elementary particles. The definition of an elementary particle is, to some extent ambiguous because particles thought to be elementary have been shown upon further investigation to have a composite structure. Furthermore many particles classified as elementary have a very short lifetime, $\tau \leq 10^{-20}$ sec so that the distinction between an energy state and a particle becomes blurred. Even more so according to our present beliefs some elementary particles, the quarks, cannot exist freely. The energy we associate with a particle of mass m is $E=mc^2$ and Fig. 1 shows on a logarithmic scale the broad range of energies covered by the elementary particles. Neutrinos, photons and some other proposed elementary particles are believed to have zero mass.

We already alluded to the fact that many elementary particles decay rapidly. An example of such a decay $\pi^0 \to \gamma\gamma$ is shown graphically in Fig. 2a. It is also important to recall that a particle and antiparticle can annihilate each other as shown in Fig. 2b. The converse is also true, namely a particle-antiparticle pair can be created from the energy available in the collision of particles; as an example in Fig. 2c we sketch the sequence $e^+e^- \to$ energy $\to$ D^+D^-. The D-meson has a lifetime of order $\tau \sim 10^{-13}$ sec, sufficient for the D's to emerge from the interaction region. To create an unstable particle of mass m, we must provide energy mc^2 in a region of space-time comparable to the size and lifetime of the elementary particles. Such conditions can be achieved only in very high energy collisions and this has led to the development of particle accelerators of ever increasing energy.

2. Particle Accelerators

All particle accelerators use an electric field to accelerate a charged particle but there is a wide variety of arrangements that can be used. For high energy physics applications circular accelerators, which originated with E. O. Lawrence's discovery of the cyclotron in 1930, have been the most successful. Major milestones were the discovery, in 1948, of phase stability, independently by McMillan and Veksler; this led to the invention of the synchrotron. Next, came the discovery of strong focusing by Nicholas Christofilos in 1950, and independently by Courant, Livingston and Snyder in 1952. Strong focusing made possible the construction of the large synchrotrons at CERN in Europe, at Brookhaven and Fermilab in the U.S. and at Serpukhov in the USSR. Recent advances in superconducting magnet construction will allow the extension of such machines to even higher energies, that is to several TeV.

Linear accelerators have certain advantages as compared to synchrotrons in particular for the acceleration of electrons, since synchrotorn radiation is absent. The largest electron Linac at Stanford, in the U.S. is 3km long and will soon accelerate electrons (and positrons) to 50 GeV. In recent years colliding beams have been used in order to reach high center of mass energies. The beams of e^+ and e^- or of p and $\bar{p}$ are stored in a single ring where they counter-rotate and are brought into collision at a few distinct points.

The tremendous progress in particle accelerators, and for that matter in particle physics, would be completely impossible without strong focusing. The credit for the first discovery and ennunciation of this principle belongs to Nick Christofilos. The greatness of his genius was such that he made his discovery alone and without the support of colleagues or of any traditional experience in particle accelerators. Fig. 3 gives the account of these events taken from M. S. Livingston's book "High Energy Accelerators"(1). Not only the dimensions of the synchrotron magnets could be reduced by a factor of 10 but the size and quality of the beams were greatly enhanced.

3. Matter and Antimatter

A consequence of Dirac's equation, which correctly describes the electron, is the appearance of negative energy solutions. We now know that these solutions must be interpreted as positive energy states describing the positron which is the antiparticle of the electron. The positron was discovered in the cosmic radiation in 1934 a few years after its theoretical prediction. It was not until 1955 that the antiproton, the antiparticle of the proton, was discovered. We now know that for every particle there exists an antiparticle, and that this is a fundamental symmetry of Nature which is strictly obeyed.*

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* Certain Bose particles can be their own antiparticles.

It is interesting that the particle/antiparticle symmetry, which was discovered and confirmed from a study of the elementary particles poses an important question for cosmology. If, as is currently believed, the universe was born in a big-bang, it should be symmetric in its particle-antiparticle content. Yet we exist in a part of the universe devoid of antiprotons.

The antiproton was discovered in a difficult and elegant experiment, performed soon after the then largest particle accelerator, the Bevatron was completed. Thomas Ypsilantis a physicist of Greek descent was one of the members of the small team of researchers that made the discovery(2). Fig. 4 shows extracts from their communication in which the existence of the antiproton was announced. The existence of antimatter has of course profound implications for our views of life, of our own existence and of the world as a whole. It is now evident that all matter can be annihilated but also that it can be created; it is also evident that we and our planet occupy a special non-symmetric place in the universe. We have here an example of how man, through a combination of theoretical and experimental research can learn about his world much more than he can perceive through his senses.

4. Quarks

Significant evidence had accumulated by the late 1960's to the effect that the proton and the neutron, the mesons and all other strongly interacting particles were composites of quarks or of quarks and antiquarks. There were three types of quarks, the up (u), down (d) and strange (s) quark. Quarks have spin 1/2 and fractional electric charge. For instance the proton is composed of three quarks p (uud) whereas the π^- meson is composed of a quark-antiquark pair $\pi^-(d\bar{u})$. In the table below we show some of the relevant quantum numbers of the constituents and of the composite system.

Table I - The quark structure of elementary particles

Proton	$p \rightarrow$ u u d			
	+2/3 +2/3 −2/3	= +1	Electric charge
	+1/3 +1/3 +1/3	= +1	Baryon number
	$1/2 \oplus 1/2 \oplus 1/2$	$\rightarrow$ 1/2	Spin angular momentum
π-meson	$\pi^- \rightarrow d\ \bar{u}$		
	−1/3 −2/3	= −1	Electric charge
	+1/3 −1/3	= 0	Baryon number
	$1/2 \oplus 1/2$	$\rightarrow$ 0	Spin angular momentum

Confidence in the three-quark model was based on the success of SU(3) in interpreting particle spectroscopy and in the success of the parton model as applied to deep inelastic scattering. In 1970 S. L. Glashow, John Iliopoulos* and L. Maiani(3) proposed a theoretical model of the weak interactions to explain the observed absence of certain decay processes. Their ingenious model involved cancellations between specific amplitudes but required the existence of four quarks. In their paper, parts of which are reproduced in Fig. 5, they predicted the existence of a fourth quark and specified many of its properties.

The fourth quark, which is now referred to as charmed (c), was experimentally discovered, rather unexpectedly, in 1974. Since then, a fifth quark, named bottom (b) was discovered in 1977; the top (t) quark which is hypothesized to be the partner to the b-quark has not as yet been observed in

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* J. Iliopoulos is a corresponding member of the Academy.

spite of intense searches. The cancellation mechanism proposed by Glashow, Iliopoulos and Maiani, known as the GIM mechanism, remains one of the important symmetries of the weak interactions and appears to be operative also for the third family of quarks.

The discovery of quarks has provided us with a rational explanation for the properties of the strongly interacting particles and has made possible a quantitative treatment of their interactions. At the same time it has raised as many new questions: for instance the spectrum of quark masses is completely unexplained, the relation of quarks to the leptons remains a mystery. With each quark family (doublet) are associated a charged lepton and its corresponding neutrino. While we believe that neutrinos are massless one cannot exclude that they may have a small mass. The present situation is summarized in Fig. 6; note that the mass scale is logarithmic. Whether, in Nature, there exist only three families of quarks and leptons or whether there are more is an open question and we have no clues to what the answer is.

5. Greece's participation in CERN

Greece has been a member of the European Center or Nuclear Research (CERN) since its formation in 1953. CERN symbolizes the spirit of technical cooperation and scientific achievement of the European Nations. A triumphant accomplishment was the discovery in 1983 of the $W^{\pm}$ mesons and of the Z° meson. These are the most massive elementary particles ever to be detected by man. Eventhough shortlived they were produced and observed in antiproton-proton collisions in the CERN colliding accelerator operating in the SPS at 270 on 270 GeV. The $W^{\pm}$ and Z° mesons are the carriers of the weak interaction and their discovery confirms, beyond doubt, the unification of the weak and electromagnetic forces.

The main effort at CERN, at present, is the construction of a Large Electron Positron collider, known by the acronym LEP. The circumference of the ring is 28km and the initial energy will be 50 on 50 GeV. A sketch of the LEP ring and its elevation are shown in Fig. 7. The SPS ring is also indicated for comparison. With the completion of LEP, the European Community is almost certain to maintain the leadership in elementary particle physics over the next decade.

It is in this spirit of European and International collaboration that young Greek scientists have ample opportunity to participate in particle physics research and to make their own unique contributions. Eventhough this field of research is highly technical, it is also distinctly pure in its goals and aspirations.

Figure Captions

Fig. 1 The range of masses of the elementary particles on a logarithmic energy scale.

Fig. 2 Diagrammatic representation of the interactions of elementary particles (a) Decay of a π^{o}-meson (b) Particle-antiparticle annihilation resulting in energy release (c) Creation of a pair of D-mesons in electron-positron annihilation.

Fig. 3 Part of p.123 from M. S. Livingston's book on "High Energy Accelerators".

Fig. 4 Parts of the article announcing the discovery of the antiproton.

Fig. 5 Parts from the GIM-mechanism paper where a fourth quark is proposed.

Fig. 6 The spectrum of quark and lepton masses for the three known families.

Fig. 7. The outline of the LEP collider presently under construction at the CERN laboratory in Geneva, Switzerland.

References

1. M. Stanley Livingston, "High Energy Accelerators", Interscience Publishers, New York 1954.
2. O. Chamberlain, E. Segre, C. Wiegand and T. Ypsilantis, Physical Review 100, 947 (1955).
3. S. L. Glashow, J. Iliopoulos and L. Maiani, Physical Review D2, 1285 (1970).

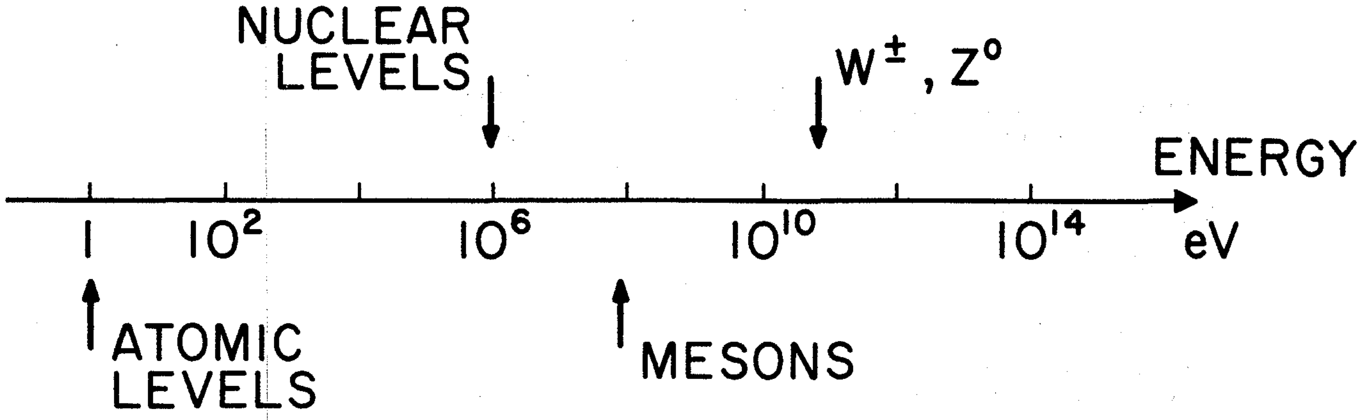
NUCLEAR
LEVELS
W±, Z0
ENERGY
1
10^2
10^6
10^10
10^14
eV
ATOMIC
LEVELS
MESONS

Fig. 1

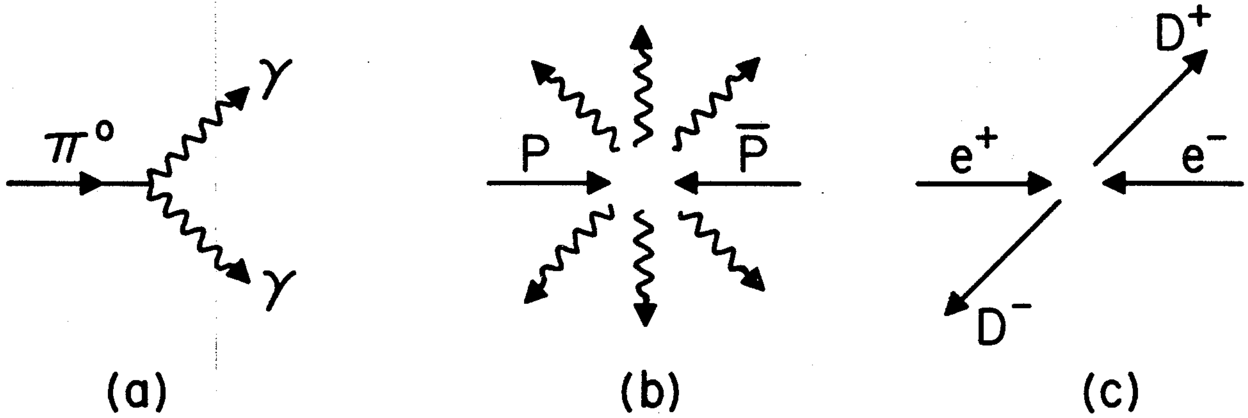
π0
γ
γ
P
P̄
e+
e−
D+
D−
(a)
(b)
(c)

Fig. 2

HIGH-ENERGY ACCELERATORS

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Interscience Publishers Ltd., London 1954

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About six months after the original article was submitted to the *Physical Review* for publication, it was called to our attention that Mr. Nicholas Christofilos, an electrical engineer from Athens, had made a study of resonance accelerators which included the alternating gradient principle. His privately printed report "Focusing System for Ions and Electrons and Application in Magnetic Resonance Particle Accelerators" is dated 1950. It is clear that Mr. Christofilos deserves credit for the earliest enunciation of the principle. It is also true that the work reported in reference 38 was independent.

Strong focusing involves the use of very much larger radial gradients in the field, of which n is of the order of hundreds or thousands instead of less than unity. These strong gradient sectors are alternated so as to be directed radially inward and radi-

Figure 3

Observation of Antiprotons*

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(Received October 24, 1955)

ONE of the striking features of Dirac's theory of the electron was the appearance of solutions to his equations which required the existence of an antiparticle, later identified as the positron.

The extension of the Dirac theory to the proton requires the existence of an antiproton, a particle which bears to the proton the same relationship as the positron to the electron. However, until experimental proof of the existence of the antiproton was obtained, it might be questioned whether a proton is a Dirac particle in the same sense as is the electron. For instance, the anomalous magnetic moment of the proton indicates that the simple Dirac equation does not give a complete description of the proton.

The experimental demonstration of the existence of antiprotons was thus one of the objects considered in the planning of the Bevatron. The minimum laboratory kinetic energy for the formation of an antiproton in a nucleon-nucleon collision is 5.6 Bev. If the target nucleon is in a nucleus and has some momentum, the

Figure 1 shows a schematic diagram of the apparatus. The Bevatron proton beam impinges on a copper target and negative particles scattered in the forward direction with momentum 1.19 Bev/c describe an orbit as shown in the figure. These particles are deflected 21° by the field of the Bevatron, and an additional 32° by magnet $M1$. With the aid of the quadrupole focusing magnet $Q1$ (consisting of 3 consecutive quadrupole magnets) these particles are brought to a focus at counter $S1$, the first scintillation counter. After passing through counter $S1$, the particles are again focused (by $Q2$), and deflected (by $M2$) through an additional angle of 34°, so that they are again brought to a focus at counter $S2$.

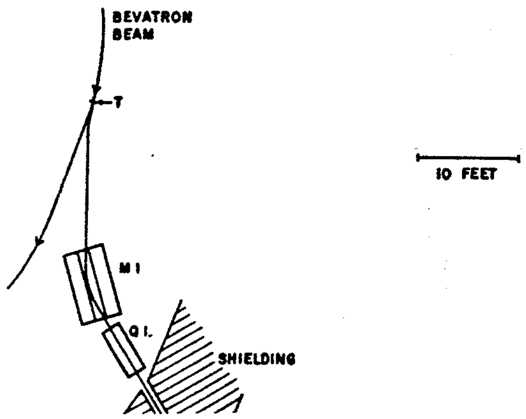

Figure 4

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Weak Interactions with Lepton-Hadron Symmetry*

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(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

I. NEW MODEL

We begin by introducing four quark fields.[10] The three quarks $\mathcal{P}$, $\mathfrak{N}$, and λ form an $SU(3)$ triplet, and the fourth, $\mathcal{P}'$, has the same electric charge as $\mathcal{P}$ but differs from the triplet by one unit of a new quantum number $\mathcal{C}$ for charm. The strong-interaction Lagrangian is supposed to be invariant under chiral $SU(4)$, except for a symmetry-breaking term transforming, like the quark masses, according to the $(4,\bar{4})+(\bar{4},4)$ representation. This term may always be put in real diagonal form by a transformation of $SU(4)\times SU(4)$, so that B, Q, Y, $\mathcal{C}$, and parity are necessarily conserved by these strong interactions.

The extra quark completes the symmetry between quarks and the four leptons ν, ν', e^-, and μ^-. Both quadruplets possess unexplained unsymmetric mass spectra, and consist of two pairs separated by one in electric charge.

$$U=\begin{bmatrix} -\sin\theta & \cos\theta \\ \cos\theta & \sin\theta \end{bmatrix}. \qquad (5)$$

This is just the form of the weak current suggested in an earlier discussion of $SU(4)$ and quark-lepton symmetry.[10] What is new is the observation that this model is consistent with the phenomenological selection rules and with universality even when all divergent first-order terms [i.e., $G(G\Lambda^2)^n$] are considered.

To see this, we proceed diagrammatically in the quark model ignoring the strong $SU(4)$-invariant interactions.[11] Zeroth-order terms occur only in diagrams with only one external quark line, and give contributions to the quark mass operator of the form

$$\delta M(\gamma k)=\sum A_n(G\Lambda^2)^n\bar{q}M_n\gamma\cdot k(1+\gamma_5)q. \qquad (6)$$

The A_n are dimensionless parameters, and the matrix M_n is a symmetric homogeneous polynomial of order

Figure 5

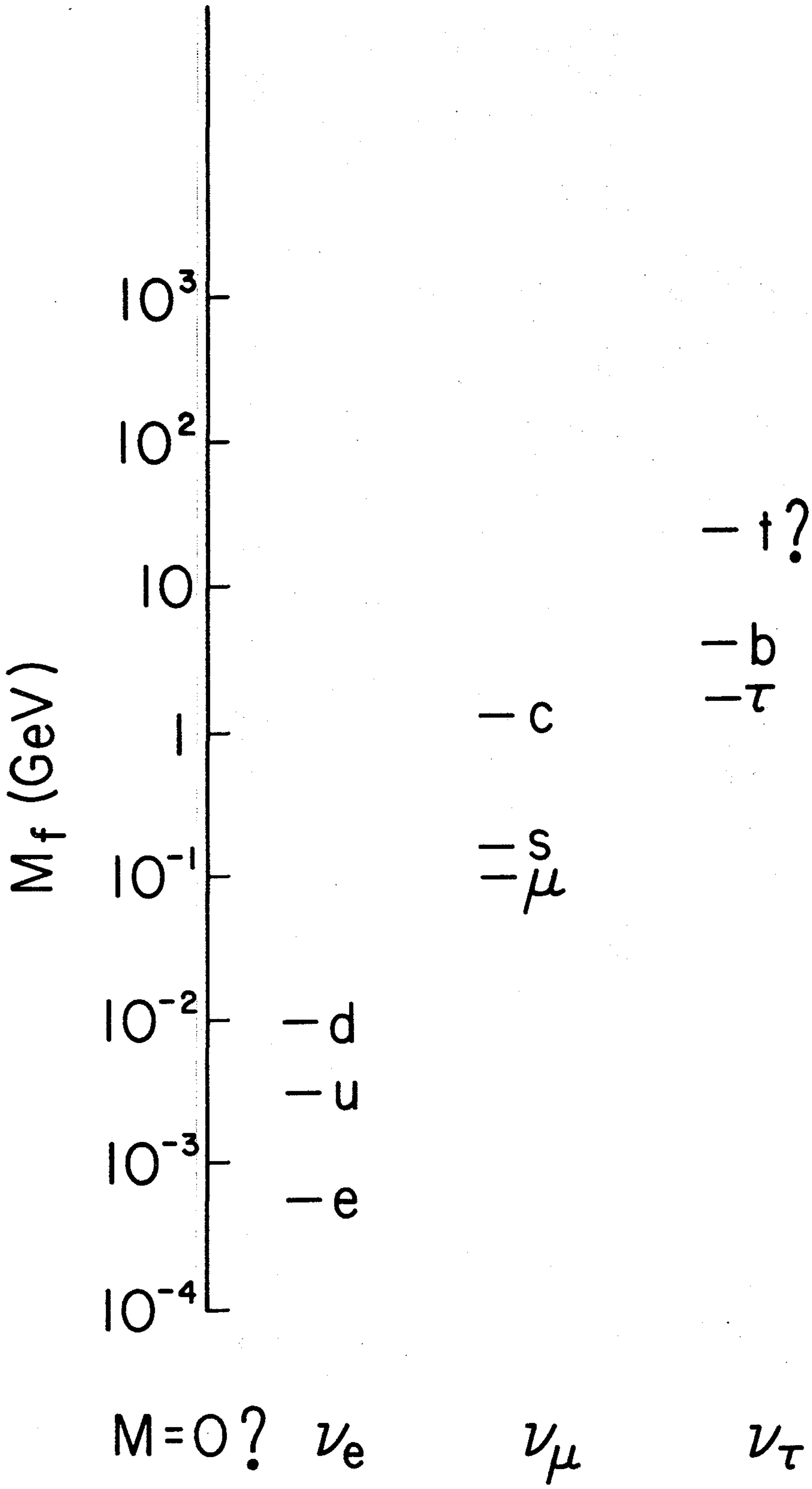
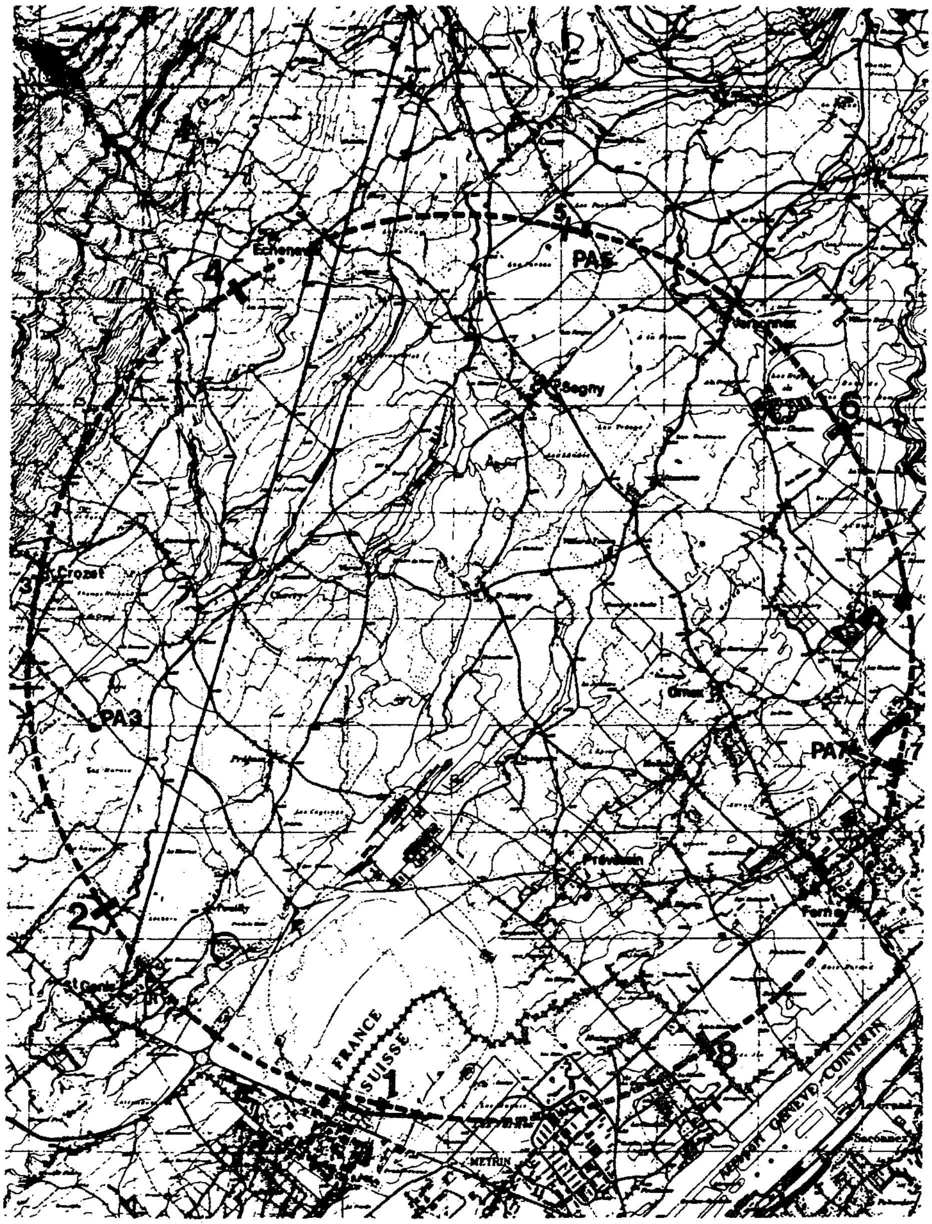


Figure 6

The new proposed location of the 27 km circumference LEP electron-positron ring at CERN. In contrast with previous proposed locations, only 3 km of tunnel passes under the Jura mountains to the north-west. The existing CERN installations would straddle the ring near the point marked '1'. The ring would pass under the French-Swiss border at four places.



CERN Courier, March 1982

1 KM.

Figure 7