6. THE FIRST PERIOD OF HIS SCIENTIFIC WORK IN ROME (1952–1960)

The first work carried out in Rome, at the beginning of 1953, shortly after his arrival, was in collaboration with M. Sands$^{61)}$ of the California Institute of Technology. Sands was in Rome on a "fellowship" awarded by the Fulbright Foundation. The work [17] followed a few months after the discovery of strong focusing$^{62)}$ and concerned the errors of magnets' alignment in synchrotrons based on this principle. The authors showed that certain ideal orbits (i.e. calculated without alignment errors), which were periodic in a single revolution, are transformed by alignment errors into open orbits which are secularly unstable. This was found to be the case in the vicinity of certain values of the betatron frequency. But far from such "resonances" there are however stable orbits. They also produced estimates for the misalignment tolerances necessary to give rise to a reasonable amplitude of perturbed motion. At the same time, similar calculations were made also by other authors$^{63)}$, who are quoted, together with that made by Sands and Touschek, in all treatments of the stability of strong focusing accelerating machines$^{64)}$.

The short paper written with E. Fabri on "The mean lifetime of the τ meson" [22] concerns a problem on which work had been started by an experimental group at the Institute$^{65),66)}$ shortly after the discovery of this new particle$^{67)}$. The problem of the possible existence of correlations between the energies of the three pions emitted during the decay $\tau^+ \rightarrow \pi^+ + \pi^- + \pi^+$ had been tackled but not solved in a general manner in 1953$^{66)}$, a time when the experimental data available were not statistically significant to provide an answer.

Touschek's work contains a detailed discussion of the relation between the mean lifetime and angular momentum J of the τ meson. In particular, the authors notice that this particle decays into two identical charged pions which necessarily should be into a state of parity P = +1 and angular momentum ℓ even, and a third pion of opposite charge and of angular momentum λ relative to the centre of mass of the two others. They concluded from this observation that the parity of the τ meson should be equal to $-(-1)^\lambda$. On the basis of certain estimates, the authors also noted that with statistically significant data it should be possible to distinguish at least the case $J = 0$ from that of $J = 1$.

This work slightly preceded that of Fabri$^{68)}$, in which the problem was re-examined in detail and clarified with the introduction of the same graph submitted a little earlier, without Fabri's knowledge, by R. Dalitz$^{69)}$ and which today is known in the literature as the "Dalitz-Fabri plot".

The "Report of the Committee on τ Mesons" [26] is the final report made by the Committee of "experts" appointed at the "International Congress on Heavy Unstable Particles and on High-Energy Events in Cosmic Rays", held in Padua during 12–15 April 1954$^{70)}$. This report, together with similar reports prepared by participants at the Congress, re-examines the situation of each of the new particles, paying special attention to the experimental values of the electric charge, mean lifetime, rest energy, and decay modes.

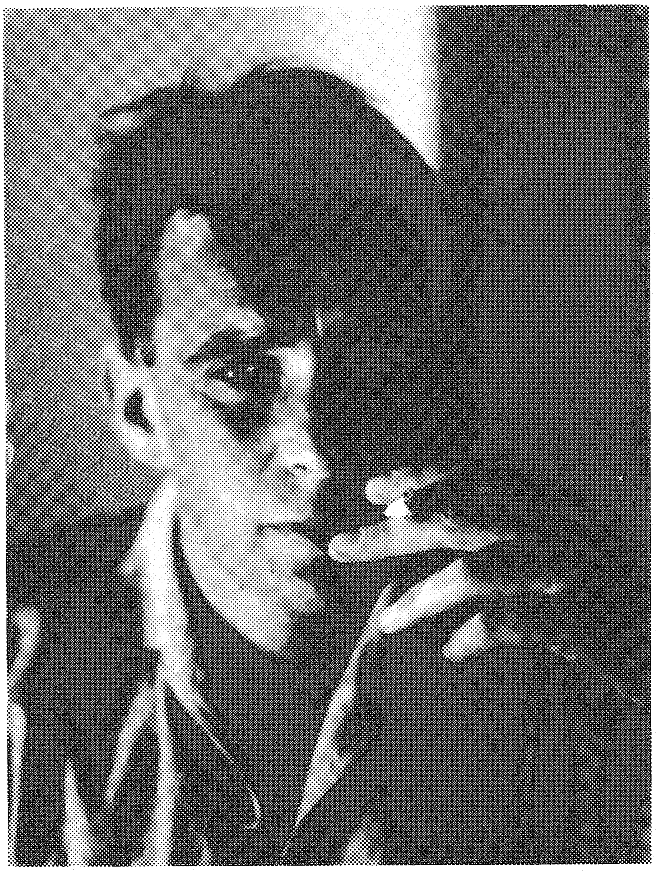
The paper [25] is a discussion, prepared by Touschek in conjunction with Fabri, on the final states produced during the capture of K particles, of which at that time only seven events$^{71)}$ had been observed, which according to Touschek could not be attributed to a single mechanism.

The paper with G. Stoppini, entitled "Phenomenological description of photo-meson production" [31] presents certain phenomenological expressions for the differential and integral collision cross-section, for the photoproduction of pions on a nucleon, valid in the region between the threshold and the first resonance ($J = 3/2, I = 3/2$).

These expressions were obtained by introducing suitable corrections to the perturbation expression, in a similar manner to that used in the Born approximation with distorted waves, which is currently used in nuclear physics. The fundamental idea is to include phenomenologically the two main causes which make the perturbation method unsuitable: i.e. the correction to the final state due to the pion-nucleon interaction (in state 3/2, 3/2) and the interaction due to the anomalous magnetic moment of the nucleon.

The expressions which the authors derived in this manner are in very good agreement with experimental results. The general trend of the paper follows the ideas by G. Chew$^{72)}$, although it differs from these in certain important details.

In addition to these papers, some of them of an engineering and others of a phenomenological nature, Touschek published during these years a whole series of papers, some of which tackle problems relating to calculation methods, whereas others deal with fundamental questions or questions of principles.



In Rome (1955)

To the first category belong papers [21], [23] and [35]. G. Morpurgo, who graduated in Rome in 1948 and went to work in Chicago in 1952, returned in August 1953 and found Touschek in Rome. He had had the idea of studying, in the case of a solvable model, such as that of G. Wentzel73), what difference there was between the exact solution and those calculated with the Tamm-Dancoff method or in the perturbation approximation. He spoke to Touschek about it; they started to discuss the problem jointly and rapidly came to the conclusion which was submitted to the Congress of the Società Italiana di Fisica, which took place in Cagliari on 23–27 September 1953, and also sent to Nuovo Cimento [21].

In this paper the authors clarify the relation between the eigenvalues of a system closed inside a box of finite volume and the phase shifts of the various waves that appear in collision theory (i.e. in the limits of infinite volume). In particular they deduce an elegant relation between the bound states and the phase shifts using the Wentzel model in S-wave.

This paper to a certain extent contributed to reducing the interest in the Tamm-Dancoff method74).

This work also led to a discussion with M. Cini during one of his trips to Rome from Turin where he was the assistant of G. Wataghin. Cini had already devoted himself to the Tamm-Dancoff method75). On that occasion Cini, Morpurgo and Touschek applied an approximate but not perturbative method, previously developed by Cini and S. Fubini76), to the solvable case of Wentzel's model and showed that, in that case, it was superior to the Tamm-Dancoff method [23].

Morpurgo and Touschek had found, when discussing between them, that there were many more fundamental difficulties in fully understanding the "time reversal" operation than in understanding the "parity" operation.

During a trip to Naples they spoke about this to L. Radicati, who had recently been appointed Professor of Theoretical Physics at Naples University. This gave rise to a collaboration between the three of them, facilitated by the fact that Radicati came to Rome each week and stayed with Touschek, who lived in a flat on the fourth floor of the mansion at No. 3 Via Saliceto.

Radicati recalls certain evenings he spent in Touschek's flat, when he was visited by various friends. The conversation, which followed an open course and was imperceptibly guided by Bruno, ranged over a wide variety of subjects, from literature to politics, painting to physics, the latter being rarely touched on, and then only lightly. During May and June, the characteristic atmosphere of the city was clearly perceptible from the terrace, where their conversation was punctuated by witticisms and ironical remarks, most of which were made by Bruno.

In the paper "On time reversal" [24], the authors made a detailed analysis of this operation within the framework of classical and quantum mechanics. This paper was amply reviewed by F.J. Dyson77), in *Math. Rev.,* who introduces his comments with the following remarks: "In the extensive literature devoted to the problem of time-reversal in quantum mechanics, this is one of a few papers which add substantially to the original discussion by E.P. Wigner ...."

There then follows a short paper by Morpurgo and Touschek [27], in which the authors provide a rigorous proof of the irreversibility of a system composed of a neutral scalar meson coupled with a nucleonic field, which had already been discussed in paper [24].

In a subsequent paper, entitled "Time reversal in quantized theories" [28] Morpurgo, Radicati and Touschek extend the considerations presented in the first paper on this subject [24] to the case of field theory.

Papers [29] and [30] by Morpurgo and Touschek are extensions of the same types of definition, techniques, and procedure to the parity and charge conjugation operations.

A final paper, also written with Morpurgo a short time after [37], entitled "Parity conservation in strong interaction", was never published, because when they received the galley profs, Morpurgo had the impression that the paper was rather trivial. They did, however, make it known by circulating it in the form of an internal report of the Institute78) and making a presentation of its essential points at a Congress held in Padua in 1957, as a comment to a paper by another author. In the paper it is shown that if one assumes invariance of the pion-nucleon system with respect to time reversal and rotation in isospin space, the invariance with respect to parity and charge conjugation also follows automatically. The same result was found by G. Feinberg as well as others some time later79).

In the various papers on time reversal, Bruno had also concerned himself with the problem of parity which was specifically dealt with in the papers "Parity conservation and the mass of the neutrino" [32] and "The mass of the neutrino and the non-conservation of parity" [33], both of which are very important, particularly the former. In the first of these two papers, Touschek is the first to introduce what was much later referred to as *chiral symmetry*. Abdus Salam80) had proposed the operation of *discrete symmetry*

$$\psi \rightarrow \gamma_5 \psi, \tag{1}$$

where Touschek introduced the operation of *continuous symmetry*

$$\psi \rightarrow e^{i\alpha\gamma_5}\psi. \tag{2}$$

He had proposed this operation in order to define the conservation of the leptonic number in the presence of parity violation, which is also the definition adopted today, for which the leptonic number of the neutrino is equal to its helicity. Later it was recognized that this continuous symmetry introduced by Touschek intervenes in a very general manner, for example in the algebra of currents, as was pointed out by Gell-Mann81).

In this paper [32], received by Nuovo Cimento on 26 January 1957, Touschek quotes the famous paper by T.D. Lee and C.N. Yang, in which it is suggested that parity is not conserved by weak interactions82); he also quotes the paper by Mrs C.S. Wu and collaborators83), announcing the experimental confirmation of the predictions made by Lee and Yang with regard to ^{60}Co decay. In fact, Touschek quotes an issue of *Time Magazine* of 28 January 1957, which appeared a few days later, in which the news was published for the first time. This suggests that the quotation was added when corrections were made to the proofs. Touschek's paper was, however, fully written, or almost so, before the experimental confirmation of parity non-conservation in weak interactions.

It should also be said that both Touschek and Salam proposed the neutrino two-component theory, and that the uncertainty between the two possible interactions (S + P + T) and (V − A) had already been solved by Touschek in favour of the latter84) in the second of the two papers discussed here, on the basis of the asymmetry observed in the decay of the muon in the paper by R. Garwin, L. Lederman and M. Weinrich on the $\pi \rightarrow \mu \rightarrow e$ process85).

At that time everything was in agreement with the assumption that the weak interaction was of the (V − A) type, with the exception of the experimental results relating to ^{6}He, which were, however, erroneous as was found shortly after. In his second paper, Bruno concludes in favour of (V − A), since only this interaction was compatible with the sign of the asymmetry observed in the $\pi \rightarrow \mu \rightarrow e$ process.

Another paper—the last in collaboration with Radicati—is entitled: "On the equivalence theorem for the massless neutrino" [34]. It concerns the magnetic moment of the neutrino. The authors show that, at the limit of the mass of the neutrino equal to zero, the magnetic moment of this particle tends to zero as a consequence of the invariance of the wave function under the operation of chiral symmetry (2).

This paper was written after Radicati had moved from the University of Naples to that of Pisa, where Bruno regularly went in order to lecture on "field theory" at the Scuola di Perfezionamento in Fisica at this University (see Section 7).

The paper written with Cini on "The relativistic limit of the theory of spin 1/2 particles" [35] links up with the two papers on the neutrino properties [32, 33], of which we have already spoken. When Touschek spoke of them to Cini, stressing the interest of the invariance of the wave function of the neutrino under the operation (2), the problem arose as to whether it was not possible to deal with the case of a particle having a non-zero mass, starting, as zero approximation, from the case of a zero-mass particle. The problem appeared, to a certain extent, as the reverse of that dealt with by L.L. Foldy and S.A. Wouthuysen86), who had developed a systematic theory, i.e. valid at all orders, for the case of Dirac particles having a kinetic energy much lower than the rest energy.

The problem solved by these two authors is to find a canonical transformation which eliminates from the Hamiltonian any uneven operator, i.e. any operator which (like the α of Dirac) connects the first two components with the second two of Dirac's spinor. Foldy and Wouthuysen had found the general expression for this transformation and shown that, when it was cast in the customary form of a perturbative series, the most important term was that of the mass.

The view taken by Cini and Touschek is the opposite: they start from the solution of Dirac's equation, valid for a momentum p vastly greater than *mc* (i.e. rigorously valid for zero mass), in which the spinor has only two components of opposite helicity, and try to find a canonical transformation which takes into account the finite value of the mass. The result is that in this case too there is a canonical transformation which separates the major components of the spinor from the small components. This transformation, expressed in perturbative form, involves operators which are both even and odd, the most important of which is $\exp\{ia\gamma_5\}$.

This formalism was developed by Cini and Touschek in view of its use for the electrons emitted in weak decays where, generally, they have a momentum p much larger than *mc*.

Papers [36], [38] and [40] concern essentially the same problems, and represent an extension of the concepts introduced in papers [32] and [33]. The most important of these three papers is [36] entitled "The symmetry properties of Fermi Dirac fields". In this paper a presentation and discussion are given of the first example of non-Abelian chiral symmetry, although it is expressed in a different form from that which is now more customary. This is probably the reason why this important result obtained by Touschek in practice has never been duly attributed to him.

The reason for this kind of presentation of the subject is that Touschek dealt with this problem taking his inspiration from Heisenberg's non-linear theory87), in which an attempt is made to construct all the possible fields starting from the Majorana-type Fermionic fields, whereas, following the discovery of parity non-conservation82), use is made of the Dirac-type fields and a separation is made from the outset between the fields of different chirality, i.e. left-handed and right-handed.

In paper [33], which has already been discussed above, Touschek had introduced the symmetry operation (2) and shown that the requirement for "free particle" fields to be invariant under such an operation is sufficient to guarantee that the mass of the corresponding particle is zero. This result is taken up and generalized in paper [38] entitled "A note on the Pauli transformation", where Touschek shows that this is applicable also in the presence of interactions. In this rather formal paper, Touschek seeks, among other things, to expound Heisenberg's theory in an axiomatic form.

7. BRUNO TOUSCHEK'S CONTRIBUTION TO TEACHING AND HIS UNIVERSITY CAREER

From the academic year 1953–54 until 1961–62, Touschek made a substantial contribution to teaching with a course he gave at the Scuola di Perfezionamento in Fisica at the University of Rome, of which he became also Vice-Director (see Section 5). This school had been set up in 1952 with the idea of creating a system in Italy which would be very similar to an American postgraduate school. For this purpose I had had lengthy discussions on this problem with various colleagues, in particular Bruno Ferretti, and had consulted Enrico Fermi and Bruno Rossi to obtain first-hand information on what was being done at the University of Chicago and the MIT58).

In the capacity of Vice-Director of the Scuola di Perfezionamento Bruno Touschek made for years a remarkable contribution to the preparation of the syllabus and the choice of the teachers, but the course he gave was even more important. The course changed its title as the years went by: "Cosmic rays and subatomic particles" from 1953–54 to 1955–56, "General particle theory" from 1956–57 to 1959–60, and then "Field theory" in 1960–61. Although different all these titles corresponded to the presentation of the same subject, i.e. elementary particle theory, which was updated every few years. In 1960–61 he also gave a six-months' course on "Particle accelerators", dealing with certain theoretical aspects of these machines, in which Bruno Touschek had at that time developed a renewed interest (see Section 9). The following year, 1961–62, he also gave a few lectures of a course in which other teachers (N. Càbibbo, M. Cini and G. Jona) participated: "Complements to theoretical physics". In the following years, however, he preferred to break off his teaching activity to have more time to devote himself fully to the theoretical and experimental research which was being carried out at Frascati and Orsay on and with AdA (see Section 9). He again took up teaching at the Scuola di Perfezionamento of the University of Rome in 1966–67 with the course entitled "Complements to theoretical physics, 2nd part" which he continued to give until 1970–71.

The courses which Touschek gave had a marked influence on many pupils as each of them graduated. Among the many who submitted their theses whith Bruno I should mention: for the "laurea" in physics, N. Cabibbo, F. Calogero, P. Guidoni (who graduated in 1958), A. Putzolu (in 1961), Giovanni Gallavotti (in 1963), Paolo Di Vecchia (in 1965), Aurelio Grilli (in 1968), and for the "laurea" in mathematics Etim Etim (in 1965) a young Nigerian who came to Italy with a scholarship from "AGIP Mineraria".

Bruno Touschek did a considerable amount of teaching at Pisa as well. He was responsible for the course on "Field theory" at the Scuola di Perfezionamento of that University in 1956–59 [66], not only to increase his income, but especially because his trips to Pisa enabled him to maintain the contacts with Radicati, which resulted in their collaboration on weak interactions [34].

Radicati recalls Touschek's brilliant and extremely clear lectures, which to a large extent followed the pattern of the course he gave on the same subject at the Scuola di Perfezionamento of the University of Rome during the years 1953–54 to 1966–67.

It was by means of these lectures that Touschek had a considerable influence on various young physicists at Pisa such as A. Di Giacomo, P. Menotti and L.E. Picasso.

Bruno usually caught a train which left Rome at 12 a.m., went to the restaurant car, where he would eat and drink without too much restraint, arrived in Pisa somewhat tipsy and then went to sleep; then, shortly after 6 p.m. he gave his lecture in full form and in a brilliant manner.

In addition to this, he was also one of the lecturers on various courses at the Scuola Internazionale di Fisica of the SIF (Società Italiana di Fisica) which were given in Varenna. There was the Sixth Course, which took place from 21 July to 9 August 1958, on the "Mathematical problems of the quantum theory of particles and fields" directed by A. Borsellino, and the Eleventh Course which was held from 29 June to 11 July 1959 on "Weak interactions", directed by Radicati. In addition, the SIF gave Touschek the responsibility for organizing and directing the Ninth Course, which was held from 18 to 30 August 1958, on "The physics of pions".

The lecture which was given at the Sixth Course [39] is also signed by W. Pauli. It is entitled: "Report and comment on F. Gürsey's 'Group structure of elementary particles'". It is a paper which is original only in part, and sets forth some considerations which Pauli had communicated to him in a letter (see Sections 1 and 2) combined with what Touschek had in essence already stated in paper [36]. Pauli had put forward the idea of trying to find very general symmetries and had applied it to the case of $n = 2$ Majorana-type Fermionic fields. In this lecture Touschek takes up the same idea and applies it to the cases with $n = 1, 2$, and 4 Majorana-type Fermionic fields, but without adding anything basically new compared with paper [36].

His inaugural lecture at the Ninth Course of the Scuola Internazionale di Varenna on pion physics, organized and directed by Touschek himself, is presented in publication [40], whereas publications [41] and [42] are lectures which he gave during this same course. Paper [41] concerns the 'Fixed source meson theory", and contains an elegant exposition of Chew's ideas72). Paper [42] concerns "Elementary considerations in photo meson production" and, in addition to providing a general statement of the problem, contains the same phenomenological considerations he had put forward with Stoppini in paper [31].

The lectures on the "Theory of the neutrino", given by Touschek at the Eleventh course of the Scuola di Varenna on "Weak interactions" is contained in publication [43] and that given to the Scuola Primaverile, organized by E.R. Caianello in Naples in 1960 [47], summarizes the discussion of the chiral transformation (2), which had already been published in papers [32] and [33].

Touschek's contribution to these courses, and especially to the Ninth Course, went, however, well beyond his own always very original and brilliant lectures. His own participation in the majority of the discussions and the observations he made quite frequently during the lectures given by other teachers were characterized by a vivacity and enthusiasm which remained imprinted in the minds of all those who attended them.

In recognition of all these contributions, the Società Italiana di Fisica awarded the "SIF prize" for teaching merit to Bruno Touschek, on the occasion of its 44th National Congress held in Palermo from 6 to 11 November 195888).

From the academic year 1960–61 to the end of 1968–69, the Faculty of Mathematical, Physical and Natural Sciences put Bruno Touschek in charge of the course of "Statistical mechanics", which had never been given before at the University of Rome. The course, which was intended for 4th year physics and mathematics students, had, like the others, a substantial influence on various students, such as Giovanni Gallavotti and Gian Carlo Rossi, the second of whom collected the lectures given by Touschek (1965–66), producing them later in the form of a book entitled *Statistical mechanics*, published by Boringhieri in 1970 [67] (Section 13).

Touschek gave up the course in statistical mechanics when, in 1969, he was appointed "Professore Aggregato" at the Faculty of Science, where he was asked to give a newly-introduced course on "The mathematical methods of physics", which he continued to give for the rest of his life. I will come back to this point later.

During the academic year 1970–71 he was asked to give a course on 'Statistical mechanics" at the Scuola Normale in Pisa, the contents of which were basically the same as those of the book which he wrote in collaboration with G.C. Rossi [67].

Finally he organized and directed the Summer School on "Physics with Intersecting Storage Rings" that took place from 16 to 26 June 1969 at Villa Monastero on Lake Como89).

Among the teaching staff I can recall R. Gatto, J. Haissinski, A.N. Lebedev, G.K. O'Neill, G. Pellegrini, M. Sands, K.G. Steffen and R. Wilson. Bruno did not give any lecture, but with his continuous presence and his extremely lively participation in all discussions instilled life into the course, which is still remembered today by all the participants as a particularly agreeable and interesting intellectual experience.

As I have already said, from the beginning of his stay in Italy Bruno Touschek held an R2 post at the Istituto Nazionale di Fisica Nucleare (INFN), which was equivalent in pay (and in prestige, but only in the restricted field of the INFN and physicists in general) to the post of Extraordinary Professor in an Italian university. The problem of getting Bruno into a State post remained unsolved for many years, since the reform of Italian schooling, introduced by G. Gentile when he was Minister of Education in 1928, had short-sightedly specified that a certificate of Italian nationality was required for candidates wishing to sit university competitions.

After the war, the physicists' community, and in particular the SIF, had on many occasions drawn the attention of the Minister of Education to the urgent need for a change in the law, in order to allow foreigners also to participate in our university competitions, as had been authorized by the Casati law of 185990). The reason for this was that it would certainly have a beneficial effect in general for the Italian universities, and because of Bruno Touschek's own specific case. Despite the fact that more than one Minister, and in particular Giuseppe Medici, was firmly convinced that this was a reasonable proposal, it had fallen by the wayside following rejection by the Consiglio Superiore della Pubblica Istruzione.

This shortcoming in Bruno Touschek's career considerably upset him—so much so that in 1959 he seriously considered applying for Italian citizenship. After all, he had already lived in our country for many years and so far had felt very happy there. He did, however, very strongly resent having to collect all the documents which are required by law for a formal application of this type. Nevertheless, I had hopes of convincing him to ask for the essential documents to be sent from Vienna. As it seemed, furthermore, that a description of his previous scientific and teaching activities might speed up the application he had to make personally, and seeing that he refused to take any action in this direction, I wrote to P.I. Dee asking him to send me an official statement concerning Bruno's activity at Glasgow University. Dee, who was not in the habit of such formalities, was rather taken by surprise, but nevertheless sent me a document signed by the registrar of Glasgow University, decorated with a few very attractive stamps! But on a return from a trip to Vienna in the summer holidays, Bruno told me that his father had got wind of the matter and asked to see his passport (which was Austrian, since he had still taken no effective action), and announced that following a discussion with his father he had decided not to apply for naturalization. I told him that I fully understood his reasons, including those of his father, and that I realized that if it was not possible to help him embark on a university career in Italy it was purely the fault of the short-sightedness of Italian law.

In order to provide a partial remedy for this situation, which had become even more intolerable because some of his Italian pupils were embarking, quite rightly, on their university careers, while Bruno was still grade R2, the INFN undertook formal measures to promote him from grade R2 to grade R1, for which the pay was the same as that of an Ordinary Professor, but which was not the same from the viewpoint of security, stability and pension, nor did it have the same social prestige.

The promotion took effect on 1 July 1963, on the unanimous approval of a commission appointed by the Consiglio Direttivo of the INFN, composed of E. Persico, B. Ferretti and G. Puppi, to examine the situations of Bruno Touschek and Ernesto Corinaldesi, who were unable to follow a normal university career because they were of foreign nationality91).

A much overdue solution to the problem of his university career was found in 1969 when the post of "Professore Aggregato" was introduced in the Italian Universities by a law where no mention is made of certificate of Italian nationality. He was thus appointed, in November 1969, Professore Aggregato to the Facoltà di Scienze M.F.N. of the University of Rome and was asked to give a course on "The mathematical methods of physics".

When, in 1973, the law came into force concerning the "Urgent Measures for the University" (law No. 580 of 1 October 1973) containing—*inter alia*—details of the transfer procedure to enable Aggregate Professors to become Extraordinary Professors, Touschek was appointed on 24 October 1973 Extraordinary Professor of "Mathematical methods of physics", on a unanimous proposal by the Consiglio di Facoltà di Scienze M.F.N. of the University of Rome.

In Italy, one normally becomes an Ordinary Professor after three years of teaching as an Extraordinary Professor. The decision is taken on the basis of the views expressed by the Faculty and a specific commission appointed by the Minister, concerning the applicant's scientific and teaching activities.

Bruno, however, refused to submit the application and the documents required by the Ministry, since he considered these bureaucratic formalities as an unbearable obligation, lacking in all consideration. All of these formal procedures, including filling in the application were finally performed by colleagues at the Istituto Guglielmo Marconi. The result was that it was not until early 1978 that the Ministerial commission could be convened and Touschek appointed Ordinary Professor.

In the meantime, however, the Accademia Nazionale dei Lincei appointed him Foreign Associate on 26 September 1972, and Bruno was highly pleased at this act of recognition, which to some extent offset the bitterness he felt towards the Italian universities.

During the sixties I got the impression on a few occasions that the very aspiration of Bruno was for a university career in Austria. Paul Urban has recently informed me that when Professor Theodor Sexl died, in

1967, Walter Thirring, who was already professor of Theoretical Physics in Vienna, proposed Bruno Touschek as Sexl's successor. At the beginning Bruno was very much in favour of such an appointment, but did not take an immediate decision and kept the Faculty in suspense for about two years. To the renewed insistences of Urban, Bruno finally answered personally: "I am from Vienna, my wife is from Scotland and therefore it is better for our children to grow up in a third country".

8. OTHER ASPECTS OF HIS NATURE AND ENJOYABLE RENEWED CONTACTS WITH HIS OWN COUNTRYMEN

Bruno Touschek was not only very keen on tennis, but also on swimming and underwater diving. Whether it was a little alpine lake, a Scottish "loch" or the lakes of Bracciano, Albano, or Nemi, Bruno was always ready do dive into the water even when the weather was far from warm. His passion for this became much greater at a later date, when his children were five or six years old and could enjoy swimming with him. He went with them in person to take swimming lessons and took an enormous delight in their progress. When he arrived at the Institute in those years he would speak to all of his friends about his children's success in sport or would give a vivid description of his own latest underwater adventure and the long, patient tactics he employed in order to catch a huge perch, which had been watching him for a long time from a creek among the rocks.

In order to keep himself and his young children in trim without having to go to public pools, he had set up in the courtyard of his flat, on the ground floor of No. 23 Via Pola, a 3 × 3 metre plastic swimming pool. Shortly after, however, he was forced to replace it by a smaller pool, because the ceiling of the garage under the courtyard was unable to carry the weight much longer.

During his conversations with his friends he referred from time to time to a few short stories of "Graf Bobby" and his friends "Baron Mucki" and "Herr Poldi", three typical figures in Austrian humour at the end of last century[92)]. They are rather decadent people who always meet the questions and circumstances of life in an inept manner or make remarks which are grammatically correct but quite illogical and inspired by detailed criticisms of all possible situations. Quite often, Bruno would re-evoke on the spot a short story featuring Graf Bobby, which was appropriate for the situation he and his friends were in at that particular moment, and would comment that he felt he was himself somewhat like Graf Bobby.

He would have a profuse supply of these remarks when he was feeling a little heady from a glass of wine that he drank adding the remark that "The superego is soluble in wine".

As Braitenberg wrote to me[5)] "in an attempt of self-analysis many years ago Bruno, a strong Freud follower (... perhaps for Viennese solidarity reasons), had noticed he had completely and irremediably lost the image of his mother. He knew he had seen her many times even when in his early 'teens'; he knew that he could count on much precise information about her existence and about the daily relations between mother and son but did not succeed in evoking her image. He believed, according to the canons of psychoanalytical orthodoxy, that from the removal of this emotion-charged complex there sprang out for the rest of his life the obscure forces which he did not feel he mastered. He refused, however, the suggestion of submitting himself to psychoanalysis. A first encounter with a Freudian psychoanalyst was not followed up. On that occasion Bruno told me he was afraid of losing the source of energy from which research stemmed, a price he was not prepared to pay for his serenity."

An event which was important for Bruno and certainly contributed to bringing him back closer to his country of origin was an invitation he received in 1975 to participate as an Austrian scientist at the "Staatsfeiertag" (State Holiday). After all, this was the first official recognition he had received from his country.

At the end of the Second World War, Austria's keen desire to reacquire independence, which was always strongly felt by at least part of the population, had been met by the formation of a national government, headed by the socialist Karl Renner and supported by a coalition of popular and socialist parties. Austria had, however, remained under Allied control, divided into four areas occupied by American, British, French and Russian troops[12)].

After long negotiations and Chancellor Raab's trip to Moscow, on 15 May 1955, the "Staatsvertrag" (State Treaty), which guaranteed Austria's independence, was signed at Belvedere Castle in Vienna by the foreign ministers of the four occupying forces and of Austria.

A few weeks later, the Republican National Council unanimously voted a constitutional law which established Austria's permanent neutrality. With this began the withdrawal of the occupational troops, ending on the 15 October 1955, with the departure of the Russian contingent.

This date is marked as the "Staatsfeiertag", which is celebrated every year and for which invitations are sent to Austrian citizens residing abroad, each time representing a different category. In 1975 it was the scientists' turn. One of the persons who helped prepare the invitations was Victor Weisskopf[93)], who had been a close friend of socialist Prime Minister Bruno Kreisky ever since high-school, where they had been members of the "Bund Sozialistischer Mittelschuler" (Socialist Association of Intermediate Schools), at the beginning of the 20's.

9. THE PERIOD OF THE e^+e^- RINGS

On 7 March 1960, Bruno Touschek held a seminar at the Laboratori Nazionali di Frascati, where he demonstrated for the first time the importance of a systematic and thorough study of electron-positron collisions (e^-e^+) and how this could be achieved, at least in principle, by constructing a single magnetic ring in which bunches of electrons and positrons circulate at the same energy E, but in opposite directions[94)]. By installing suitable particle detectors near to the parts of the ring where the bunches of opposite sign intersect, it is possible to study the particles emitted in all the reactions produced at the centre-of-mass energy $2E$, since the centre-of-mass of the two colliding particles is stationary in the laboratory reference frame (Fig. 1a).

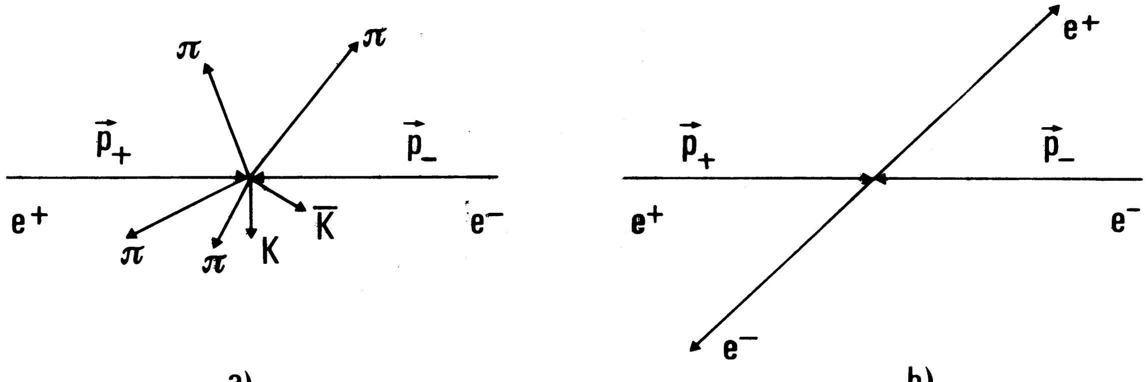


Fig. 1 Various processes are observed in e^+e^- collisions:
(a) production of $n \geq 2$ hadrons (π, ρ, K, ...);
(b) elastic scattering e^+e^-.

As I will clarify below, the talk of Bruno was more elaborate. It contained, however, already in this first part, two of the various arguments which made his proposal interesting:

i) It made it possible to obtain a considerable *kinematic advantage* for any process between particles. One of the most important parameters of such a study is always the relativistic invariant $W = \sqrt{s}$, i.e. the energy in the centre-of-mass of the two colliding particles. In the case of the usual accelerators in which a particle of mass M_1, energy and momentum E_1 and $\vec{p}_1$, collides with a particle of mass M_2 at rest, one has

$$W = \sqrt{(E_1 + M_2c^2)^2 - c^2\vec{p}_1^{\,2}} \tag{3a}$$

which, for $E_1 \gg M_1, M_2$ becomes

$$W = \sqrt{2M_2c^2E_1} \quad , \tag{3b}$$

which shows that W grows in proportion to the square root of the energy E_1 given by the accelerator to the incident particles.

In the case of two particles that collide with equal and opposite momenta ($\vec{p}_1 = -\vec{p}_2$) one has

$$W = \sqrt{(E_1 + E_2)^2 - c^2(\vec{p}_1 + \vec{p}_2)^2} = E_1 + E_2 \tag{4a}$$

If the two particles have the same mass so that $E_1 = E_2 = E$, one has

$$W = 2E \, , \tag{4b}$$

i.e. W goes up in proportion to the energy of each of them.

This aspect of the problem had been already pointed out by Kerst et al.[95)] and O'Neill[96)] in 1956. These authors, however, had considered only the case of e^-e^- collision obtained with the bunches of electrons circulating in opposite directions in two magnetic rings tangent to each other at a point where the collisions take place[97)].

None of the articles of the two American groups mention the work done by Wideröe and of which I shall talk below.

Following O'Neill's proposal[96),97)], a group at Stanford University had even started to design and construct a machine of this type[98)], which was the first one producing very interesting scientific results on the e^-e^- collision[99)].

ii) If the circulating particles have equal and opposite electrical charges, a considerable *constructional advantage* is obtained because a *single* magnetic ring can be used in which the particle bunches circulate in opposite directions. Also this point had been made by Wideröe who, years before, had discussed it with Touschek.

In his talk Touschek emphasized, however, two other important aspects of his proposal.

iii) The electron-positron system (i.e. e^-e^+) has the same quantum numbers as a neutral boson, so that at high energies it should become an electromagnetic particle source which is especially useful for studying strong interactions and electrodynamics. It also offered a number of various possible "two-body reactions", i.e. reactions in which, starting from the initial state e^+e^-, a final state is reached in which there is only one electron and one positron (elastic collision), or only two other particles, since the initial electron and positron disappear simultaneously owing to annihilation.

iv) Touschek also pointed out that, in any process which begins with the annihilation of a particle and its antiparticle (of initial equal and opposite momenta: $\vec{p}_+ = -\vec{p}_-$), the relativistic invariant q^2, known as four-momentum transfer, is always time-like, i.e.

$$q^2 = -(E_+ + E_-)^2 = -4E^2 < 0 \quad , \tag{5}$$

i.e. it enters a region of values which can be reached only through a few other processes in which e^+e^- pairs are produced by a (real or virtual) photon[100)] or in hadron-hadron collisions[101)].

The interest of processes of the first of these types was indicated in 1961 also by S. Drell and F. Zachariasen[102)].

Two other arguments in favour of this line of research that were not indicated by Touschek but recognized years later, are the following:

v) The detailed study of storage rings has shown that these machines have an extremely high energy resolving power

$$\frac{\Delta W}{W} = 10^{-3}.$$

It is just this extraordinary property that has made possible a detailed study of extremely narrow resonances such as the J/ψ, ψ', etc.

vi) As it was clearly understood only many years later[103)], the e^+e^-collision opens up the possibility of studying two-photon processes (Fig. 2)

$$e^+ + e^- \rightarrow e^+ + e^- + X \tag{6}$$

in which the particle X produced has the value $c = +1$ of the charge conjugation quantum number. This is a line of investigation of great interest for the 1980's[104)].

All of the arguments discussed by Touschek, and their brilliant exposition, made a considerable impression on everyone present, including the then Director of the Laboratori Nazionali di Frascati, Giorgio Salvini, and Carlo Bernardini, Gianfranco Corazza and Giorgio Ghigo.

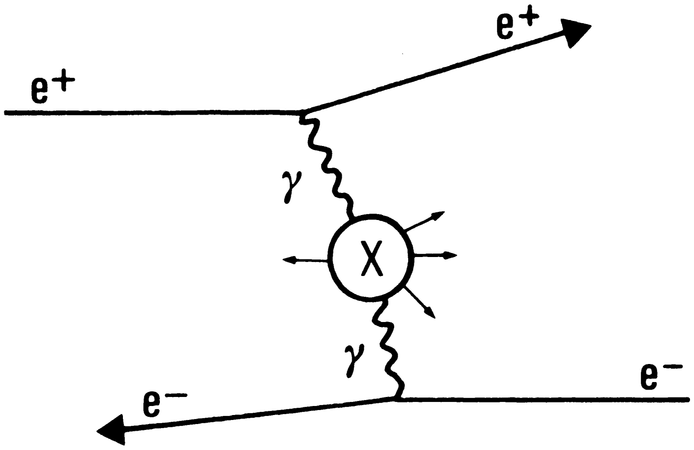


Fig. 2 Two-photon mechanism in e^+e^- interactions.

During the same day, the three last-mentioned persons began to work with Touschek on a project for the first e^-e^+storage ring, essentially designed as a protype for checking the feasibility of accelerators based on the ideas set forth by Touschek during the seminar.

This first machine for the study of collisions between a particle and an antiparticle was known as AdA (Anello di Accumulazione e^+e^-). The story of its design, construction and use has already been written about in detail by people who worked with Touschek during those years[105,106], and consequently only the main headings will be described here.

Touschek had, therefore, immediately found his first collaborators, but had also quickly found the financial resources. Giorgio Salvini, who had immediately realized the importance of the proposal, succeeded, shortly after this, in obtaining from the CNEN (of which Felice Ippolito was Secretary-General) an extraordinary grant of 20 million lire for the construction of the AdA prototype. This sum was almost entirely spent on the construction of the magnet, which was designed in a few days in a very original manner by Giorgio Ghigo[107] and produced with the assistance of G. Sacerdoti. A description of the project is set out by Ghigo in an internal note of the Laboratori Nazionali di Frascati, dated 8 December 1960[108].

It should first be said that the idea of constructing machines based on the collision of two particle beams, instead of one particle beam which strikes a fixed target, was devised for the first time by Rolf Wideröe in the late summer of 1943, during his holiday at Tuddal, near Telemark in Norway[22]. As Wideröe wrote himself:

"On a nice summer day I was lying on the grass seeing the clouds drifting by and then I started speculating what happens when two cars collide. If we have a car moving with the velocity v colliding with a resting car of equal mass, the dissipated energy will be $1/4\ mv^2$ (inelastic collision), whereas two cars with the velocity v having a head-on collision would dissipate four times as much energy (mv^2) is spite of having only twice the energy before the collision. This clearly demonstrated that head-on collisions have to be avoided for cars, but might be very useful for protons[109].

"When I discussed this idea with Touschek later, he did not appear very impressed at the moment. All he said was 'It is something obvious and trivial and cannot be patented'."[22] But Wideröe nevertheless managed to obtain a patent in May 1953[110], when he had already been working for many years in the Brown Boveri research laboratories in Baden, Switzerland. This was some three years before Kerst et al.[95] suggested, independently, that use should be made of the collision of two equal particle beams, such as a proton-proton or electron-electron beam, circulating in two different magnet rings.

In his patent, Wideröe discussed collisions between equal particles (proton-proton), and different particles (proton-deuteron), or particles of opposite charge (electron-nucleus, in particular electron-proton), suggesting various possible systems for the magnetic rings illustrated by four different figures. The collision always occurs in a ring (Reaktionsröhre): in the case of particles bearing an opposite charge, these are kept on their orbit by the magnetic field itself. In the case of particles of equal charge, Wideröe suggests the utilization of electric fields, but does not give any details about their design.

A person who seems to have come to appreciate, at about the same time as Touschek, the importance of point i) (kinematic advantage) and, for the e^+e^-case, point ii) (constructional advantage) is G.I. Budker (1918–1977)[111] of Novosibirsk, as he himself stated on various occasions subsequently[112], and as is confirmed by the rapid construction of the VEPP 2 machine[113]. The other attempts by Budker and the Stanford-Princeton group always concern machines composed of two tangential rings for e^-e^- collisions[114].

As Wideröe wrote[22]: "It was only after Touschek had 'broken the ice' with his small AdA and later on with ADONE that people got really interested in this principle. Today it is one of the leading ways to study elementary particles".

The AdA project is described in the paper by Bernardini et al. [46], from which I have taken Table 1, and the few further details given below.

Table 1

Some characteristic parameters of AdA [46]

Magnet weight	8.5 t
Outside diameter	160 cm
Number of straight sections	4
Useful magnet gap	5 cm
Cavity frequency	147.2 MHz
Energy of each beam	200 MeV

With AdA it was possible to attain a maximum centre-of-mass energy W of 400 MeV (or slightly less), which could be obtained only with a beam of positrons having an energy $E_1 = 160$ GeV in collision with the electrons of a fixed target. This example shows, amongst other things, the kinematical advantage [point i)] of intersecting-beam machines over fixed-target machines.

AdA's energy was more than sufficient to give rise to three important two-body processes:

$$e^+ + e^- \rightarrow \begin{cases} e^+ + e^- \\ \mu^+ + \mu^- \\ \pi^+ + \pi^- \end{cases}$$

But it was not, in fact, possible to study them owing to the extremely low number of electrons and positrons circulating in AdA.

The electrons were injected with a beam of γ-rays produced with the Frascati electron synchrotron. The beam was directed at a metal target inside AdA's high-vacuum chamber, and produced e^+e^- pairs. The electrons of one sign were captured in a closed orbit and were then bunched and accelerated by the RF system. Those of the opposite sign were deflected by the magnetic field towards the outside of the machine and were lost. Once the electrons of one sign had been injected, the whole machine, together with its base, which was equipped with wheels (Fig. 3), was moved along a track at right angles to the beam, until it had covered a distance sligthly larger than the orbit diameter. In this new position, the injection of electrons of opposite sign was repeated, using a second metal target located symmetrically with respect to the centre of the magnet. With this injection the electrons approached the equilibrium orbit, as a result of radiation losses starting from the metal targets which lay slightly outside the equilibrium orbit.

Touschek discussed the theory of this injection procedure in an internal note of the Laboratori Nazionali di Frascati [45].

As the work progressed, the group was expanded with the addition of three new collaborators (U. Bizzarri, G. Di Giugno, and R. Querzoli) and the support of experts in the field of RF cavities (A. Massarotti and M. Puglisi) and magnet construction (G. Sacerdoti).

Fig. 3 Photograph of AdA mounted on its movable support.

AdA began operation on 27 February 1961 [48], a date which had a special meaning for Bruno, since it was on that day a few years earlier that his aunt Ada had passed away.

This initial result had required the solving of certain complicated technological problems, especially that of constructing a chamber with a vacuum of not more that 10^{-9} Torr. With his pioneering work on the production and measurement of vacuums up to 10^{-11} Torr, Corazza succeeded in fulfilling this requirement which was essential for the circulation of electrons for a time long enough to allow the construction of this type of machine. The operating level of the machine was described very precisely by Touschek himself during a lecture on storage rings which he gave to the Centro Linceo Interdisciplinare (see Section 14):

"We had stored 80 electrons (or positrons) (one never knew which, since the discussions on signs were unending and conflicting). The work of measuring the decay curve was left to Peppino Di Giugno alone, at that time the youngest member of our '*équipe*'. At 7 a.m. I received a phone call: 'There are still eighteen left, can I kill them?' My reply can be easily guessed. It was the experimental proof that it was possible to obtain mean lifetimes of many hours, in this particular case, five hours, which was essential in order to attain significant intensities for sufficiently long periods to allow the measurement of the collision cross-section of the various processes."

The presence of even a small number of electrons circulating in the machine was determined by using a photomultiplier to observe, through a plastic window, the synchrotron light emitted tangentially to the orbit in one of the "straight sections" of the machine, where, in fact, the average radius of the equilibrium orbit was not infinite but simply twice that in the quadrants. Figure 4 shows part of the recording of the output of the photomultiplier, where one can clearly see the sharp changes due to the loss (down steps) or capture in the orbit (up steps). The synchrotron light emitted by a *single electron in orbit* could in fact be seen through a telescope, as could, incidentally, easily be calculated from the electron energy ($E = 200$ MeV), the curvature radius of the orbit and the fact that the period taken by the electrons to make one turn [at a velocity which differed from c only by $(m_e c^2/E)^{1/2}$, i.e. one part in 800] was about 14 nanoseconds. A similar recording to that shown in Fig. 4 was sent to me by Touschek on the morning following the second night of AdA's operation, and during the next night I myself went to see with my own eyes the synchrotron light which was emitted by a single electron. Bruno took an immense pleasure in showing this phenomenon which, to a certain extent, was commonplace, but at first sight appeared incredible. His enthusiasm was extreme when P.I. Dee and his wife made a trip to Rome at that particular time.

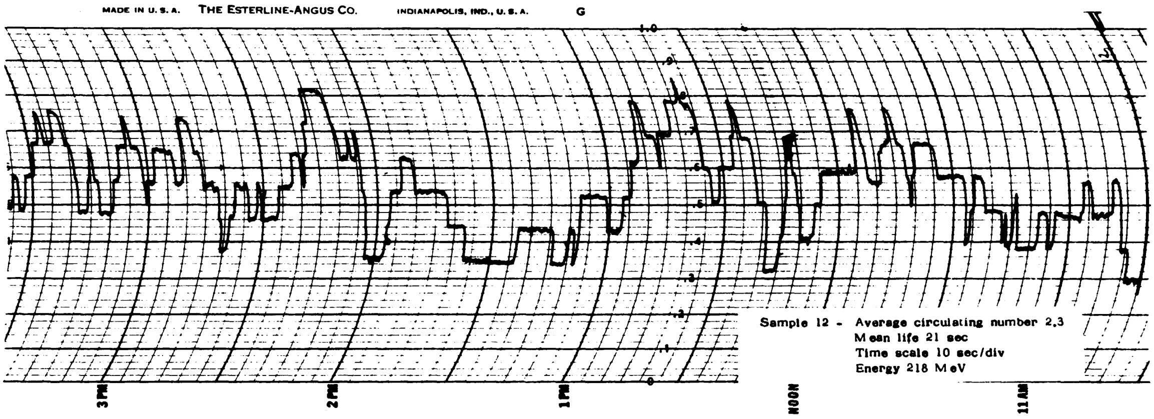


Fig. 4 Recording of the current of the photomultiplier used for observing the light emitted by single electrons circulating in AdA.

A significant experiment on e^+e^- collisions could not, however, be made with such an inefficient injection system as that offered by the facilities available at the Laboratori Nazionali di Frascati. Appropriate arrangements were then made with Orsay Laboratory near Paris, where there was a linear accelerator producing electrons up to 1 GeV, which was obviously much more suitable as an injector for AdA. In the summer of 1962, AdA was "moved to France over the Alps on a large 'truck'; the vacuum chamber was blanked off and the titanium battery-fed pump kept in operation at a pressure which did not exceed 10^{-8} Torr during the trip. The only problems encountered were with the Customs Officers (who were understandably surprised)." 106)

At Orsay the Frascati group was joined by Pierre Marin and François Lacoste. The latter collaborated for a short while but then left the laboratory to devote himself to other research work, and was replaced by Jacques Haissinski, who, with his Docteur ès sciences thesis, remains the best biographer of AdA105).

At Orsay, AdA was installed in an intermediate station (the 500 MeV "salle de cible") of the linear accelerator (LINAC), which, when operated in the correct manner, allowed the injection of 4300 electrons (positrons) per second, at a medium LINAC intensity of 0.5 μA.

The first experiment to be carried out at the machine's new location was to make extremely careful measurements of the mean lifetime τ of the bunches circulating in the machine. The new measurements, however, carried out at the beginning of 1963 at 195 MeV per beam, showed a new phenomenon which very soon became known as the "Touschek effect" |52|.

The Italo-French group found that the results of the measurements of the mean lifetime of each beam could be represented with good accuracy by the expression

$$\frac{1}{\tau} = \frac{1}{\tau_0} + aN \quad ,$$

where τ_0 is the mean lifetime measured when the bunches of electrons have a very low density, and N is the number of particles contained in the beam. They also found that the coefficient a depended very much on the energy

$$a \sim E^{-9/2}$$

(for E in the 100–200 MeV range). As C. Bernardini[106)] writes: "Touschek found the mechanism of the phenomenon by spending one night working on it (during which he went away from the room in which we lived, distraught by the din of the RF system's fans and the chattering of the internal telephone with the LINAC operators who were a very long way away). He observed that: i) the problem had to concern a mechanism within the circulating bunches, ii) it should be a collision effect, since the loss was proportional to the number of pairs of electrons in a bunch. He then observed that, by describing the stability of the beams in terms of a three-dimension potential well, the longitudinal walls of the well were much lower than the transverse walls and consequently the transfer, owing to collision, of the transverse energy into longitudinal energy necessarily resulted in electron losses. An approximate calculation immediately gave the correct expression for τ, in the 100–200 MeV range; we then completed the theory of the effect by extending it to each

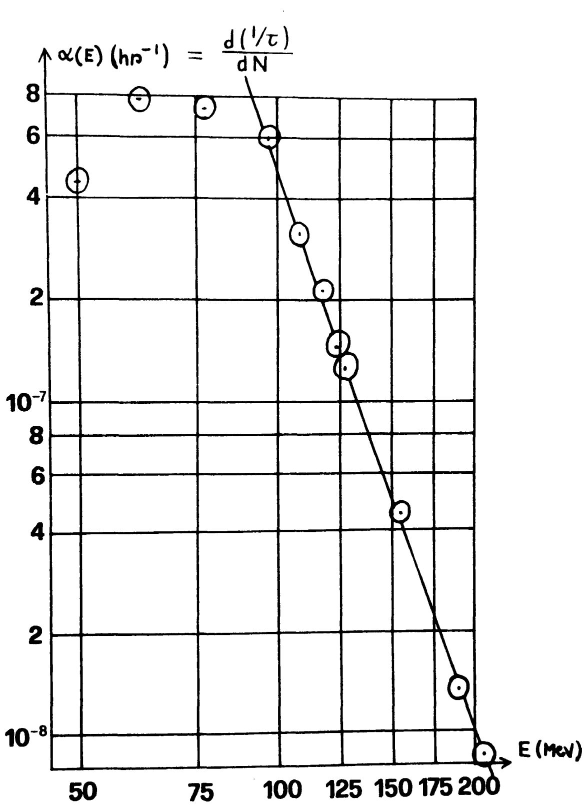


Fig. 5 Comparison of the theory of the "Touschek effect" with experimental data. (Touschek's original drawing.)

energy (Fig. 5). The immediate conclusion was, however, that since the loss was comparable with the injection velocity for $N = 4 \times 10^7$ incident particles, we were unable to go beyond this level (at 200 MeV) and in fact even at $2\text{–}3 \times 10^7$ particles saturation had been virtually attained."

Since the effect concerned was due to collisions between particles belonging to the same bunch, one way of reducing it was to decrease their density without reducing their number. In other words, it was necessary to increase the volume of the bunch. Since the vertical dimension was much smaller than the horizontal dimension, it was possible, by coupling the betatron oscillations between the two modes, to "boost" the beam during the whole injection period, i.e. when the effect was most harmful. This result was obtained by means of a quadrupole coil and orienting its axes in a suitable manner[106]. In this way, the Italo-French group succeeded in increasing the mean lifetime of the bunches by a factor of three.

The initial programme, which was to demonstrate experimentally that two beams could be made to intersect successfully and observe the e^+e^- collision, was based on the revelation, in coincidence, of the two γ-rays emitted in the process.

$$e^+ + e^- \rightarrow \gamma + \gamma.$$

The cross-section of this reaction is, however, too small to be observed even with the intensity of the beams produced at Orsay. Touschek's group consequently resorted to observing single bremsstrahlung

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma, \tag{7}$$

the cross-section of which is 1000 times greater than that of the former process.

In order to distinguish the γ-rays emitted in reaction (7) from those diffused by the residual gas, Touschek and his collaborators took advantage of the fact that the γ-rays diffused by molecules of gas only move forward with respect to the direction of the incident electrons. It follows that the number of photons C revealed per unit time is linked to the numbers N_1 and N_2 of particles present in the two beams by the relation [53]

$$C = aN_1 + bN_1N_2, \tag{8}$$

valid when the gamma-rays are revealed in a forward direction with respect to beam 1. The first of the two terms on the right of Eq. (8) represents the contribution from the residual gas, and the second the effect of the e^+e^- collision. It follows from Eq. (8) that

$$\frac{C}{N_1} = a + bN_2 \quad , \tag{9}$$

i.e. the ratio C/N_1 must be a linear function of N_2, namely of the intensity of the other beam. From measurements of this type, Touschek's Italo-French group succeeded in determining the parameter b (Fig. 6), thus demonstrating that the electrons belonging to the two beams did effectively interact [53].

In the period devoted to the experimentation on and with AdA, Bruno participated with extraordinary intelligence and efficiency in all the various phases of the work. In particular he prepared with great care the machine runs, writing a detailed programme of the measurements to be made, and at the end of the run, he always summarized the work done in order to have a clear and ordered view of the results. Figure 7 shows, as an example, the first page of one of these "Summaries of Results" after a few runs made at Orsay.

During the summer of 1963, the Brookhaven National Laboratory held the "1963 Summer Study on Storage Rings, Acceleration and Experimentation at Super-High Energies", at which Touschek presented a report [50] entitled "The Italian storage rings". At about the same time, C. Bernardini submitted, on behalf of the Frascati group, a report to a Dubna symposium entitled "Lifetime and beam size in electron storage rings" [54], which was referred to in a brilliant article on the symposium entitled "The accelerators of the future", which appeared in *Pravda* on 25 August 1963.

The interest in the e^+e^- storage rings was now extremely keen not only in Frascati but also in many other laboratories.

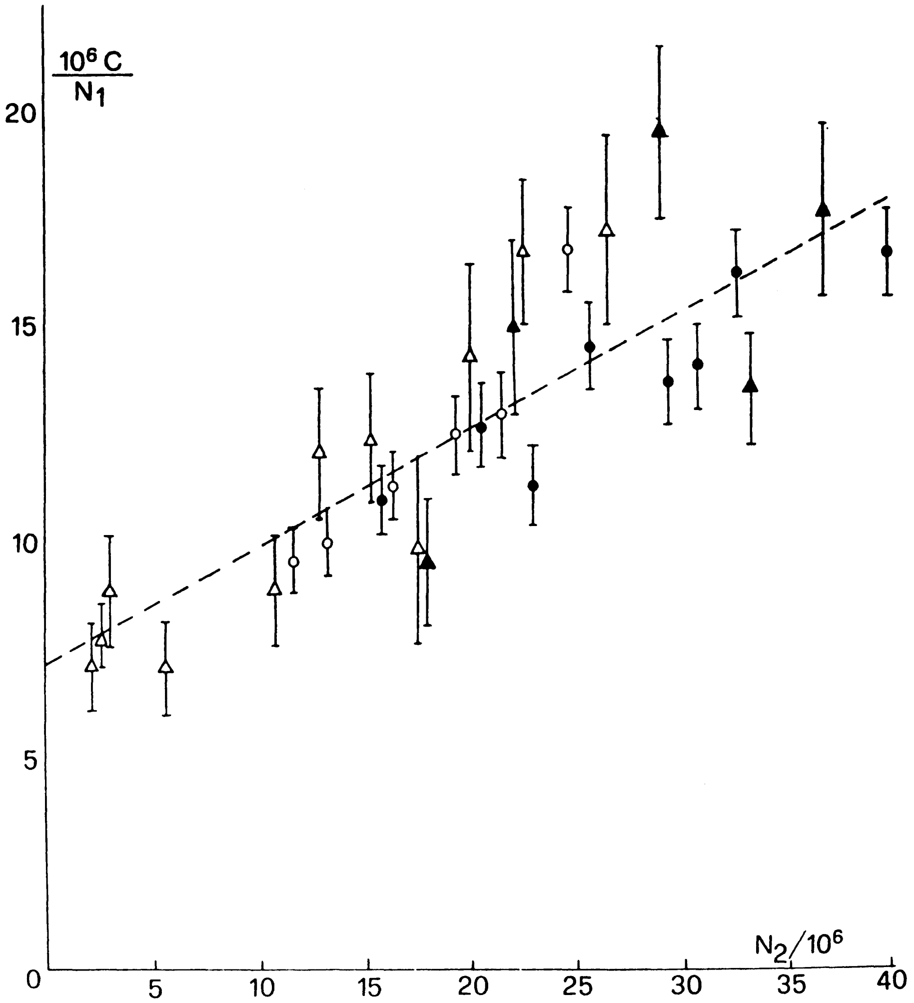
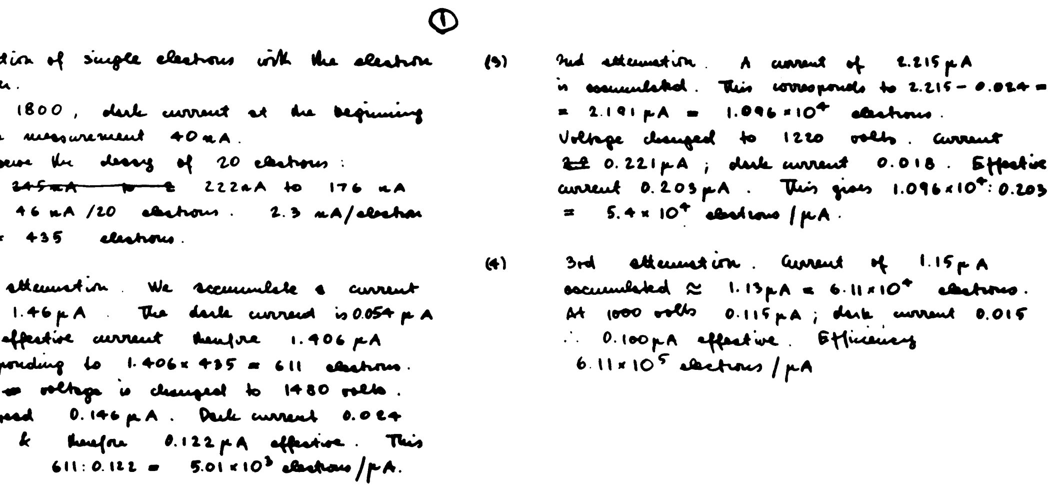


Fig. 6 Counting rate C per particle (C/N_1) in a bunch as a function of the number of particles in the opposing bunch, N_2. (Touschek's original drawing.)



①

(1) Observation of single electrons with the electron
counter.
HV = 1800, dark current at the beginning
of the measurement 40 nA.
We observe the decay of 20 electrons:
from ~~245 nA to 2~~ 222 nA to 176 nA
∴ 46 nA /20 electrons. 2.3 nA/electron
1 μA = 435 electrons.

(2) 1st attenuation. We accumulate a current
of 1.46 μA. The dark current is 0.054 μA
the effective current therefore 1.406 μA
corresponding to $1.406 \times 435 = 611$ electrons.
The voltage is changed to 1480 volts.
We read 0.146 μA. Dark current 0.024
nA & therefore 0.122 μA effective. This
gives $611 : 0.122 = 5.01 \times 10^3$ electrons/μA.

(3) 2nd attenuation. A current of 2.215 μA
is accumulated. This corresponds to $2.215 - 0.024 =$
$= 2.191$ μA $= 1.096 \times 10^4$ electrons.
Voltage changed to 1220 volts. Current
~~2.2~~ 0.221 μA; dark current 0.018. Effective
current 0.203 μA. This gives $1.096 \times 10^4 : 0.203$
$= 5.4 \times 10^4$ electrons/μA.

(4) 3rd attenuation. Current of 1.15 μA
accumulated ≈ 1.13 μA $= 6.11 \times 10^4$ electrons.
At 1000 volts 0.115 μA; dark current 0.015
∴ 0.100 μA effective. Efficiency
6.11×10^5 electrons/μA

Fig. 7 Part of the summary of the conclusions reached in a few machine runs made at Orsay, hand-written by Touschek.

Already in the course of the same year, 1960, at the Laboratori Nazionali di Frascati a start was made, under the direction of Fernando Amman115), on the design of ADONE (great AdA), which was planned for extending the study of the processes generated in e^+e^- collisions up to centre-of-mass energies $W = 2E = 3.0$ GeV. In Section 11 I shall come back to the contribution made by Touschek to this programme.

In 1964 in Orsay a decision was taken to construct ACO, an e^+e^- strong-focusing ring for a centre-of-mass energy of $W = 2E = 1.1$ GeV116). Its rapid construction and operation were possible also because of the existence in that laboratory of the already-functioning linear accelerator, which was used for the injection of the electrons.

In 1965 a modification of the Cambridge Electron Synchrotron (CEA) of Harvard-MIT was also decided in order to rapidly dispose of two e^+e^- colliding beams117) at $W = 2E = 5.0$ GeV (Table 2).

In Section 12 I shall come back to the later development of the line of research based on e^+e^-storage rings, considered from a general point of view.

10. BEAM STABILITY AND RADIATIVE CORRECTIONS

Touschek's "experimental period" had thus come to an end, although this was not true of his interest and participation in the development of the e^+e^- rings. For a few years more his attention was concentrated on two fundamental problems also in connection with the design and construction of ADONE. The first was the problem of the stability of the electron and positron ultrarelativistic beams, and the second was that of radiative corrections.

The first work on beam stability was made in collaboration with C. Bernardini [44] and dates back to 1960, in other words the period prior to the construction of AdA. It concerns the losses incurred by the electron bunches which circulate within a synchrotron at a velocity close to that of light. As has already been said, the fact that the electrons in a bunch are not rapidly lost during the motion is represented by a potential well which moves at the velocity of the centre of mass of the bunch and in which the electrons remain trapped. Both the problem of the longitudinal (synchrotron) oscillations and that of the transverse (betatron) oscillations are dealt with in this manner, except that the potential well related to the longitudinal oscillations is much shallower and shows a sharp edge (stability limit) which depends on the radiofrequency voltage amplitude. Naturally, the containment of the beam is never complete, and there are always electron losses which it is very important to calculate.

The problem was tackled by R.F. Christy118), who had calculated the losses due to synchrotron oscillations. Matthew Sands, who was also at Caltech, had carried out certain measurements on the electron synchrotron of that laboratory, and had communicated his experimental results119), which disagreed with Christy's predictions, to Fernando Amman. The latter started to take a few measurements with the Frascati electron synchrotron and found that, in agreement with Sands, the losses were considerably higher than those computed by Christy.

Informed by Amman, Bernardini began to work on the theory of this problem; pretty soon, Bruno Touschek joined him and the problem was quickly solved by their joint work.

For low excitation the quantum levels of the electrons inside the potential well are essentially those of a harmonic oscillator. But as the excitation increases, an ever-increasing anharmonicity appears since the top of the potential well becomes closer. The levels, however, are generally so close to each other as to form a continuum.

The transition from one state to the other are due to the recoil caused by the emission of the photons of the synchrotron light. Bernardini and Touschek tackled the problem as a diffusion process, described by a Fokker-Planck equation, and reached the conclusion that the loss of electrons was mainly determined by processes involving a large number of quantum jumps, whereas those calculated by Christy, which involve one or a few transitions, provide a much lesser contribution. In their work, Bernardini and Touschek derive the expression for the lifetime of a bunch of electrons in terms of the attenuation of the synchrotron oscillations and a parameter, between zero and one, related to the amplitude of the potential provided by the synchrotron's resonant cavities.

The paper written with E. Ferlenghi and C. Pellegrini [56] concerns the instability of a circulating beam of electrons caused by signals transmitted by the actual bunches to the walls of the chamber (and to various components of the high-frequency cavity, all conductors). These signals generate currents, which in turn produce fields that have a delayed phase effect on the beam bunches.

These instabilities, due to the wall's resistivity, had been observed at MURA120) and later in a few proton synchrotrons. The theory had been elaborated by L.J. Laslett, V.K. Neil and A.M. Sessler121) for the ISR (Intersecting Storage Rings) of CERN. Touschek, Ferlenghi and Pellegrini extended the theory to the more complex case of bunched beams.

The other problem, closely related to experiments on the reactions produced in e^+e^- rings, was that of the radiative corrections, where Touschek was assisted by various young collaborators. The first approach to this complex problem is set out in the thesis of Gian Carlo Rossi, who graduated with Touschek in 1966. The case concerned two beams moving in directions which formed between them an angle slightly less ($\sim 15°$) than 180°.

Touschek's general idea was to find a reasonable compromise between a strictly defined geometry of the final state, in which the radiative corrections could be calculated more easily but are, in terms of percentage, large, and an open geometry in which the corrections are smaller but difficult to calculate since they involve many perturbation orders.

The problem was tackled more thoroughly in collaboration with Etim Etim [57], and subsequently extended, and to some extent concluded, in the subsequent work with Etim Etim and G. Panchieri [58].

The case under consideration is the calculation of the cross-section observed experimentally in the processes involving the production of a particle A and its antiparticle Ā, i.e. processes of the type

$$e^+ + e^- \rightarrow A + \bar{A},$$

where A can be a muon, a K meson, or some other particle.

In the case, for example, of a K meson, if the initial energy $W = E_+ + E_-$ is equal to or greater than the rest energy of the ϕ meson ($m_\phi c^2 = 1020$ MeV) the production of $K^\pm$pairs takes place essentially by passing through the intermediate stage "ϕ", i.e. in accordance with the scheme

$$\begin{gathered} e^+ + e^- \rightarrow \phi + n\gamma \ (n = 1, 2, ...) \\ \phi \rightarrow K^+ + K^-, \end{gathered}$$

and the collision cross-section observed experimentally is given by the product of two factors

$$\sigma_{\exp} = \sigma_0(\phi;\omega) \cdot p(\omega), \tag{10}$$

where the first factor is the collision cross-section for production of the resonance ϕ, and the second represents the radiative correction, i.e. the probability of emission of any number of photons whose total energy is $\omega = W - m_\phi c^2$. As Bruno said, "If the radiative corrections are not properly administered, the collision cross-section $\sigma_{\exp}$ diverges".

The approach developed by Bruno and his collaborators in these papers is based on the use of the Bloch-Nordsieck[122)] method, and consists of a procedure which makes it possible to summate the contributions due to the emission of $n \geq 2$ photons in the limit for very low values of both the energy of the actual photons and of the resolving power of the instruments used to detect them.

By very simple reasoning, it is found that in the first order the following formula is valid

$$\sigma_{\exp} \simeq \sigma_0 \left(1 - \beta \ln \frac{W}{\omega}\right) , \tag{11}$$

which was used by various authors. In Eq. (11) ω is the resolving power expressed as total energy of the emitted photons. This logarithmic dependence of $p(\omega)$ on ω is an obvious consequence of the fact that the bremsstrahlung spectrum is of the type $d\omega/\omega$. However, as we shall see shortly, Eq. (11) is incorrect by a large factor.

In papers [57] and [58], Touschek and his collaborators showed that by summing over all the possible orders (i.e. over all the processes in which any number of photons is emitted of global energy ω) Eq. (11) is replaced by the exact expression

$$\sigma_{\exp} = \sigma_0 \cdot \omega^\beta . \tag{12}$$

$\beta = \beta\,(W,\omega,\theta)$ is a function calculable in the individual cases, which, for $v \rightarrow c$, assumes values close to $\beta = 0.07$.

Introducing into Eq. (12)

$$\omega^\beta = e^{\beta \ln \omega} = 1 + \beta \ln \omega + ..., \tag{13}$$

we immediately see that the radiative correction calculated to the first order is very much over-valued. The expression (13) contains the factor $\beta \simeq 0.07$, which Bruno Touschek, with his own particular jargon, referred to as the "Bond factor" [123)].

11. THE CONTRIBUTION OF TOUSCHEK TO ADONE

From an examination of the publications and other printed documents, the person interested in the historical development of the e^+e^- rings might be led to think that Bruno Touschek had only a marginal role in the design and construction of ADONE. And this would seem strange, having in mind how profoundly and directly he had been involved in the construction and experimentation on and with AdA. As Fernando Amman wrote to me[124)]: "One should say first of all that at the beginning (1960) the liaison between the AdA group and the embryo of what later became the ADONE group had been rather tight, and this through the action of Bruno, Carlo Bernardini and Gianfranco Corazza; the first theoretical competences on the ring, as well as the technological competences (in particular for the vacuum) evolved in a closely interknit manner. The contacts were very tight during the ADONE design phase (1963–64) which coincided with the measurements on AdA. In this period, the key figure in the liaison work was Gianfranco Corazza, whose role in both projects has perhaps not yet been adequately underlined.

"I should here recall the profound link between Bruno and Gianfranco. The latter was the person whom Bruno trusted most for his capacity to overcome any technological obstacle. To this one should add that the calm and reassuring nature of Gianfranco was the best complement to Bruno's creative anxiety.

"Bruno lived intensely the various phases of ADONE: the design as well as the construction period (1965–67) and especially the difficult year 1968 during which various beam instabilities were studied and cured. We did not meet frequently, but with regularity. Bruno was afraid of causing me to waste precious time, as he would say to C. Bernardini, and therefore followed almost daily the activity of the group, keeping in contact with Gianfranco Corazza. He was afraid of the dimension of ADONE: he considered it an enterprise of industrial type and with this he justified his reverential awe; but at the same time he felt that this was really the materialization of his original idea. Whenever a new problem came up on which he was certain to be able to contribute, Bruno was present, without the need to look for him; an example was the case of the transverse instabilities (1965).

. . . .

"Much time and effort was devoted by Bruno to the Committee for Experimentation with ADONE which started to operate in 1966; in this body he was a strong believer in the importance of a preparation of the experimental equipment adequate to the machine, but at the same time he was against all-embracing and monopolizing approaches. I think that altogether this has been an experience considered negative by Bruno in the sense that it led to foreseeing those difficulties in the use of the machine that actually occurred later."

Between the tendency to assign all, or almost all, the available resources to a single group that thus could have disposed of high-performance equipment and the opposite tendency of dividing the same funds between various groups, each by necessity endowed with an apparatus of limited performance, it was certainly not easy to find the right compromise! The solution finally adopted involved an excessive fragmentation of the financial means, with consequences not completely favourable from the scientific stand-point, and a certain disappointment to Bruno Touschek and Fernando Amman.

"What I would like to underline" continues Amman, "and I hope with this not to distort the perspective of the merits of single persons, is the substantial unity of the AdA-ADONE enterprise well beyond the official documents; this unity was achieved through the contributions of Bruno, Carlo Bernardini, Gianfranco Corazza, Ruggero Querzoli (and myself). As regards the part of which I had the direct responsibility, ADONE, I am absolutely convinced how important this unity was in proceeding in a difficult enterprise in far from ideal conditions (I recall that after Medici there was the difficult period of Lami-Starnuti as President of CNEN, and then that of Tanassi!)[125)]. This support and collaboration inside the Laboratories was assured by Bruno, Carlo and Querzoli; I feel also indebted for all that I learnt during the first years of AdA, which was of great utility to me in the subsequent period.

"How does Bruno fit into all that: he was the initiator, but also the element of continuity during the ten golden years of the Laboratories, the person that had a great idea and allowed it to be materialized by others; his scientific and human qualities, I believe, were decisive in maintaining the connections which have been essential in achieving success; if success there has been, or in the limits in which there was success. For these reasons I believe that one should accord to Bruno a primary role in the adventure of the electron and positron storage rings, an adventure that saw the emergence on the international level of an Italian laboratory more than that of individual Italian physicists....

"The epilogue of this adventure was not consistent with its beginning for a series of reasons among which the contestation in Frascati was the most apparent, but certainly not the only one; the seeds were already perceptible in the meeting of the Commission for the Experiments with ADONE that took place before 1969, in which started to appear the difficulty of organizing a serious and coherent experimental effort of Italian groups in Frascati due in part to financial limitations and to the competition from CERN.

. . . .

"This first operation of ADONE with a single beam started on 8 December 1967, and during the course of 1968 the instabilities were studied and cured. In April/May 1969 the first measurements of the luminosity of the two beams were made. The machine was then opened for the installation of the straight sections for the experiments and the protest movement started while we were closing the vacuum system (this work was actually completed in the subsequent days when the Laboratory's activities were stopped) and precisely Friday 30 May 1969. The more or less regular operation was resumed on 19 September 1969."126).