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BRUNO TOUSCHEK: PARTICLE PHYSICIST AND FATHER OF THE e^+e^- COLLIDER

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Bruno Touschek: particle physicist and father of the e^+e^- collider

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Abstract. This article gives a brief outline of the life and works of the Austrian physicist Bruno Touschek, who conceived, proposed and brought to completion the construction of AdA, the first electron-positron storage ring. The events which led to the approval of the AdA project and the Franco-Italian collaboration which confirmed the feasibility of electron-positron storage rings will be recalled. We shall illustrate Bruno Touschek's formation both as a theoretical physicist and as an expert in particle accelerators during the period between the time he had to leave the Vienna Staat Gymnasium in 1938, because of his Jewish origin from the maternal side, until he arrived in Italy in the early 1950s and, in 1960, proposed to build AdA, in Frascati. The events which led to Touschek's collaboration with Rolf Widerøe in the construction of the first European betatron will be described. The article will make use of a number of unpublished as well as previously unknown documents, which include an early correspondence with Arnold Sommerfeld and Bruno Touschek's letters to his family in Vienna from Italy, Germany and Great Britain. The impact of Touschek's work on students and collaborators from University of Rome will be illustrated through his work on QED infrared radiative corrections to high energy e^+e^- experiments and the book *Meccanica Statistica*.

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1 Introduction

Bruno Touschek was born in Vienna on February 3rd, 1921 and died in Innsbruck, on May 25th, 1978. He was the theoretical physicist who had the vision to propose the construction, and bring to completion, the first electron-positron storage ring, in Italy in 1960. In barely one month, between February and March, Touschek explored the feasibility of experimenting the physics of e^+e^- annihilation processes and prepared the actual design for AdA [1], whose name comes from the italian acronym Anello di Accumulazione, namely storage ring. He then went on to propose a bigger and higher energy machine named ADONE [2], where multiparticle production was first observed [3] and the discovery [4, 5] of the J/Ψ was confirmed [6]. The history of AdA and ADONE, and how they came to be, both in the mind and in the actions of Bruno Touschek, is a story which passes through all of Europe, in a geographical and historical sense as well. Through this brief outline of Bruno Touschek's life, we shall see how European scientists overcame the past and built a new world of knowledge and discoveries.

The major source on Touschek's life and scientific work is the biography written by Edoardo Amaldi, published as a CERN Report in 1981 [7], and, in its Italian version, in Quaderni del Giornale di Fisica [8], one year later. Amaldi's work is unchallenged in its breadth and completeness. However, thirty years have passed since this biography appeared, and, although Bruno Touschek's figure and accomplishments have been the subject of many articles and works, most of these are in Italian, and Touschek's name is only vaguely remembered by physicists outside Italy. Some perspectives have also changed. The great colliders which would definitely establish the Standard Model of elementary particles, as we know it at the beginning of LHC era, had not started operating when Amaldi wrote his biography, and fundamental discoveries, like those of the W and Z bosons in the 1980s, had not yet taken place. Another important source on Touschek's life is Rolf Widerøe's autobiography, edited by Pedro Waloshek and published only in 1994 [9]. Widerøe's autobiography contains many long passages about his relationship and his work with Touschek during the war years. In addition, as we describe in detail in the subsection of this introduction dedicated to the sources, new material has appeared which sheds light on some periods of Touschek's life.

1.1 General outline

Touschek's life can be roughly divided into four main periods, which span through the Second World War, and were spent in different European countries, namely in Austria, where he was born, in Germany both during and soon after the war, in Scotland, Glasgow, where he obtained his doctorate, and then in Italy from 1953. After moving to Italy, other important travels in his scientific and personal life include a period in France, at Orsay in 1962 and 1963, a few months at CERN in Geneva, during his last year, and the final return to Austria, where he died in May 1978.

In order to understand the relevance of Touschek's scientific contributions and put him in a historical perspective, we start Sec. 2 by recalling the major discovery of the J/Ψ in 1974, and then focus on the birth of electron-positron collisions, describing Touschek's early years in Rome and how the proposals to build AdA and ADONE came to be. We shall highlight the importance of Touschek's work on electron-positron storage rings, positioning his work in Frascati within the international background efforts. Using unpublished documents and letters from the Archives in Rome and in France, we will include a description of the second stage of AdA's work, which took place at Orsay and confirmed the feasibility of electron-positron colliders. This section includes also a brief reminder of the work on electron-positron colliders taking place in Soviet Union around the same time. As for the contemporary American efforts, which led to the construction of the Stanford Positron-Electron Accelerating Ring (SPEAR), which discovered the J/Ψ, we refer the reader to the complete and detailed description found in [10]. For more details on AdA's birth and the early work in Frascati we shall refer to [11–13].

In Sect. 3 we go back to the period in Bruno Touschek's life between the time he had to leave the Vienna Staat Gymnasium, because of his Jewish origins from the maternal side, until he arrived in Italy in 1952. During this time he met Rolf Widerøe in Germany in 1943, and started working with him on the theory of the betatron. We shall present an in-depth discussion of the early years , 1938–1947, spent between Austria and Germany. These years include the war period, and the years in Göttigen, where he obtained his diploma in physics and established a relationship with Werner Heisenberg. We will then illustrate the years 1947–1952, when he moved to Glasgow, Scotland, where he received his Ph.D. and where he remained as a lecturer until the end of 1952, when he moved to Rome University. These different periods of his life reflect the unusual circumstances under which he studied and became both a theoretical physicist and an expert in accelerating machines. A number of previously unknown documents, which give new insights and provide a key to understand much better the distinctive nature of his later scientific activity, will be discussed in Subsect. 1.2, dedicated to the available sources.

In Sect. 4 we illustrate Touschek's work in Rome after the proposal to build AdA and ADONE, and describe his work on radiative corrections to high energy electron-positron experiments, summarizing the development of soft photon summation in QED and its relevance to present day physics. We shall also mention another instance of Bruno Touschek's influence on the development of research in theoretical physics at Sapienza University of Rome,[1] through the book *Meccanica Statistica*, with some comments kindly provided to us by Touschek's student and co-author G. Rossi.

In Sect. 5, in order to complement the narrative of Touschek's war years, we publish the complete translation of the two post-war letters describing Touschek's imprisonment in Germany and the shooting incident which occurred on the way to the Kiel concentration camp in Spring 1945.

Bruno Touschek had inherited from his mother an artistic bend, which, coupled to his unique sense of humor, often produced remarkable comments on contemporary life. We show in Fig. 1 one such drawing as well as a 1955 photograph of Bruno Touschek in Rome. Some of his best known drawings can be found in [7,8]. In Sect. 6 we reproduce a short selection of unpublished drawings, recently made available to us by Touschek's family.

Our present work is not, nor could be, an alternative to [7,8]. Our aim is to highlight some aspects of Touschek's life which complement Amaldi's work, through Touschek's personal papers and the newly found material contributed by Touschek's family and with a new perspective on Touschek's contribution to particle physics through the work of his students and collaborators.

[1] Sapienza University of Rome was simply known as University of Rome until 1981, when a second State University was established in Rome, in Tor Vergata, and the old name of "La Sapienza" was reintroduced in common usage.

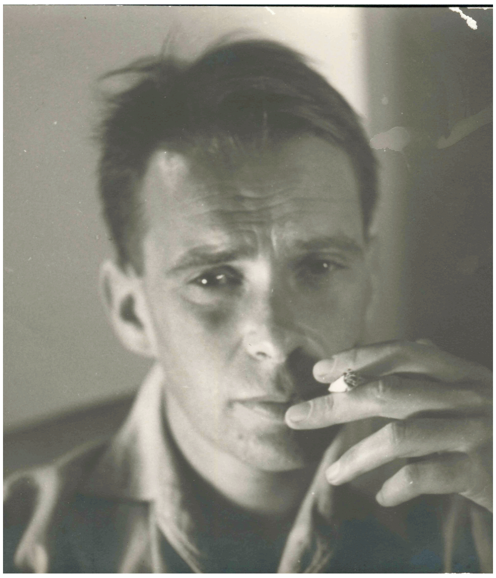


Fig. 1. A drawing of T.D. Lee by Bruno Touschek on the left and, on the right, Bruno Touschek in Rome in 1955.

1.2 Available sources

To prepare this article we have made use of both secondary and primary sources. The major published source about Bruno Touschek is Edoardo Amaldi's work [7,8], based on information from Bruno Touschek himself and from his friends and collaborators. When Bruno's health started failing in the spring of 1978, Amaldi gathered Bruno's recollections of his life prior to the arrival in Italy in a set of notes, which he started on February 28, 1978.[2] These notes, drafted under Touschek's supervision, are maintained in the Amaldi Archive in the Physics Department of Sapienza University of Rome and constitute the first nucleus of the basic work on Bruno Touschek's life. Other publicly available sources with extensive material can be found in a collection of memories by scientists who had known Bruno Touschek in Rome or in Geneva [14]. New material with direct video interviews was collected during the preparation of the movie *Bruno Touschek and the art of physics* [15].

Information on the events which led to Touschek's work on the betatron can also be found in Widerøe's autobiography [9], which was not available to Amaldi. Some of the material concerning Bruno Touschek's work on the first European betatron and the war years, was known to Amaldi through the letters sent by Widerøe to Amaldi in 1979, in response to his queries about Touschek's life, and can be found in [7]. Widerøe's authobiography however throws light on other relevant aspects and we have made use of it in preparing this article. Likewise, other important sources of personal recollections about Touschek are contained in the correspondence between Amaldi and a series of people who had known Bruno Touschek during his life in Germany and in Glasgow. Together with other documents, these letters are preserved in Amaldi Archive, and of course were not used in their entirety in [7,8]. We have made use of this

[2] "[Today] at 13 I have gone to see Bruno Touschek at La Tour Hospital, in Meyrin [...] Bruno has started to tell me a part of his life and I have taken some notes, which I am relating here in an attempt to reorganize right away what he told me in his extraordinary Italian, incisive and concrete [...]". Typescript in Amaldi Archive, Physics Department, Sapienza University of Rome, Box 524, Folder 6.

source, but have also accessed other sources which had not been available to Amaldi. In preparing the biography, Amaldi was not able to use Touschek's scientific papers which were collected and catalogued only in subsequent years. A complete catalogue of these papers, maintained in the Physics Department of Sapienza University in Rome, has been published only in 1989 [16].

A major novel primary source on Touschek's life is material obtained courtesy of Touschek's family and still preserved by his wife, Mrs. Elspeth Yonge Touschek, who has kindly made it available to the authors of this article. This material, which had never been examined before, includes so far unknown personal documents from his life prior to the war, a great number of drawings and, notably, more than 100 letters sent by Touschek to his father and stepmother during the period 1939–1971.[3] These letters, generally very long and detailed, have been very important in establishing the precise chronology of certain crucial periods in Touschek's life, as well as for understanding his early formation as a physicist.

Excerpts from Touschek's letters to his father throw new light on his initial involvement with the project of the German betatron and his collaboration with Rolf Widerøe. Using these letters and other family documents, we have been able to clarify some contradictions between Touschek's biography by Amaldi [7,8] and other published sources. In such instances, as highlighted below, Touschek's letters, as the oldest primary documents, have been used to establish the sequence of events.

A source of confusion has been the year in which Touschek, as a private external student, obtained his high school diploma (*matura*), which we can now place in February 1939. Other contradictions include the date when he left Austria and moved to Germany under Arnold Sommerfeld's protection, the date of Touschek's imprisonment at the end of the war, and the shooting accident on the way to the Kiel concentration camp. Amaldi is dating Touschek's imprisonment at the beginning of 1945, whereas Widerøe in a letter to Amaldi dates it in November 1944 and, in his autobiography, November–December 1944.[4] This confusion is clarified by Touschek's letters, one dated March 13, 1945, which is the last received by his parents before being arrested for espionage, and two post-war letters, dated June 22nd and November 17th, 1945. These letters give a detailed, occasionally day by day description of the period between March 13th and April 30, when he was set free, and establish the sequence of events during the dramatic months preceding the end of World War II.

A series of letters exchanged during the 1950s with Wolfgang Pauli during the 1950s, is preserved in Pauli's Archive at CERN. Together with other scientific correspondence Touschek had at the time, notably with Max Born and Werner Heisenberg, they highlight Touschek's relationship with the fathers of modern physics in Europe. Courtesy of the Deutsches Museum in Munich, we have also retrieved a small group of letters exchanged with Arnold Sommerfeld between the end of 1941 and the beginning of 1942. These letters, which are mainly on scientific issues, throw new light on his previously known relationship with Sommerfeld, and on the latter's role in helping Touschek to move from Vienna to Hamburg where he could continue his studies and have his first research experiences, and where nobody knew of his Jewish origin.

In addition to the above sources, various articles about the history of science in Europe after the war [17] and of accelerator physics in Italy [11–13,18–25] shall also be recalled in other sections of this article.

At the end of this Introduction, we note that Touschek's publications have also been an important source of information on his scientific achievements and we have

[3] The letters are usually addressed to the parents, occasionally only to the father.

[4] Touschek himself, in a *Curriculum Vitae* prepared after 1970, states to have spent in prison the first four months of 1945.

referred to some of them in connection with specific episodes. We refer the interested reader to Amaldi's biography [7,8] for the complete list.

2 Touschek and the AdA proposal

2.1 When it all came together

On November 11th, 1974 the simultaneous announcement of the discovery of the J/Ψ [26] by two research groups [4,5] led respectively by Sam Ting and Burt Richter, opened a new era in particle physics. This far reaching discovery was made at a traditional proton machine in Brookhaven National Laboratory and at a relatively new type of accelerator, the electron-positron collider SPEAR in Stanford Linear Accelerator Center (SLAC). The discovery was confirmed three days later by the Italian physicists in Frascati [6], who, following a telephone call from the United States,[5] immediately started searching for the new particle at the Frascati storage ring ADONE.

Although Frascati[6] had been a pioneer in electron-positron collisions, the Frascati electron-positron collider ADONE had been designed to operate at a lower energy than SPEAR, and, indeed at an energy below the J/Ψ. It took a second telephone call, this time from the West coast [27], to give the exact indication of how far one needed to push the machine energy to see the incredibly high counting rate which signaled the presence of a very narrow resonance at $\sqrt{s} = 3.1\ GeV$ and thus confirm the discovery. Ten days later, a second, somewhat more massive particle (the Ψ'), clearly related to the first one, was discovered at SLAC, and many other discoveries followed in rapid succession. What has come to be known as the "November Revolution", showed that matter-antimatter collisions in a laboratory setting could compete with the traditional proton machines and were a formidable tool for discovering new particles. From then on, experiments performed at electron-positron machines consolidated thinking about basic forces and about quarks as building blocks of matter, and changed approaches to performing experiments in high-energy physics.

ADONE had been built in Frascati following an earlier, smaller, prototype named AdA. Both names carry with them Touschek's sense of humour. When the name AdA was chosen, Touschek wrote "My aunt Ada (which is short for Adele) had just died, so that one could now justly say with conviction 'Ada is dead long live AdA'," whereas the name ADONE (Italian for Adonis) for the higher energy machine which followed AdA in Frascati, suggested higher energy and much bigger dimensions, as well as an aspiration to beauty.[7]

The road leading to matter-antimatter collisions in the laboratory, had been laid out thirty years earlier, when two European scientists, the Norwegian Rolf Widerøe and the Austrian born Bruno Touschek, had met in war-ravaged Germany, collaborating on the building of a 15 MeV betatron. As recalled in his autobiography [9], it was Rolf Widerøe, who first thought of having two beams of particles collide head-on

[5] From [26] one reads: "On November 11 we telephoned G. Bellettini, the director of Frascati National Laboratories [in Italy], informing him of our results. At Frascati, they started a search on 13 November and called us back on 15 November to tell us excitedly that they had also seen the J signal [. . .]".

[6] The Frascati National Laboratories, founded in 1957 by INFN, the Italian Institute for Nuclear Physics, will be hereafter generically referred to as "Frascati".

[7] B. Touschek, "A brief outline of the story of AdA", excerpts from a talk delivered by Touschek at the Accademia dei Lincei on May 24, 1974 (typescript, B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 92.5).

in order to maximize the energy available, and even patented his idea at the time.[8] He discussed the matter with Touschek during one of their meetings, but it was Touschek, who, in early 1960, applied the idea of the kinematic advantage to beams of particles of opposite charges and actually proposed and built, in Frascati National Laboratories, the first electron-positron storage ring, named AdA, the Italian acronym for Anello di Accumulazione, literally Storage Ring.

The story of this achievement is an illustration of how physics ideas start and develop.

2.2 Italy and the construction of AdA

At the beginning of the 1950s, modern physics in Italy was resurging after the disasters of the war, building its post-war blossoming on the tradition established during the 1930s by personalities like Enrico Fermi, Bruno Rossi, Franco Rasetti, and their pupils and collaborators, among them Edoardo Amaldi, the youngest of the group. Fermi left Italy in 1938, while Amaldi remained and, after the war, together with Gilberto Bernardini,[9] took upon himself the task of reconstruction of Italian physics. In 1949, when Amaldi became director of the Guglielmo Marconi Physics Institute in Rome, he was already a leading figure for the reemergence of physics in Italy and in Europe. In the 1950s he played a major role in the birth of CERN and the European Space Agency, as well as in promoting scientific research and science policy at an international level [28]. The fullfilment of Fermi's dream of having an accelerator and a laboratory for nuclear research [29] became Amaldi and Bernardini's plan for reconstruction, and a project for the construction of a 1100 MeV electron synchrotron was put in action. The project was led by the 33 year old Giorgio Salvini, who would later become the first director of the National Laboratories built in Frascati near Rome during the second half of the 1950s.[10] Touschek's arrival in Rome in these years became one of the building blocks of the fullfilments of these dreams.

Touschek had often come to Rome because of the presence of his maternal aunt Adele, named Ada. Visiting from Glasgow in 1951, he hoped to spend a sabbatical year in Italy.[11] On September 15, 1952, he was officially offered a position by Edoardo Amaldi, within the newly founded Istituto Nazionale di Fisica Nucleare (INFN).[12]

[8] See original copy of the patent, submitted on September 8, 1943, which at the moment was kept secret and appeared only after the war. "Gleichzeitiger Umlauf von negativen und positiven Teilchen (Kernreaktionen)" preserved in Ernst Sommerfeld's personal papers at Deutsches Museum Archive, NL148,001. Arnold Sommerfeld's son Ernst, was an engineer and a lawer specialized in patenting.

[9] Gilberto Bernardini, 1906–1995, was the first president of the INFN from 1953 to 1959. He directed the CERN Proton Synchrotron experimental research group in the period 1957–1960, and was one of the founders of the European Physical Society and its first president until 1970.

[10] G. Salvini, born in 1920, from 1965 until 1971 was president of INFN, founded in 1953. In 1959 he gave a series of physics lectures on public television, which stimulated university enrollment in physics and are still remembered by that generation. He has been President of the Accademia dei Lincei and Italian Minister for Research.

[11] During the summer of 1951 he had been in Rome, and enquired about the possibility of what he felt might be a stimulating sojourn in Rome. See Bruno Touschek to his parents from Glasgow, november 8, 1951 (Bruno Touschek's personal papers preserved by Elspeth Yonge Touschek).

[12] E. Amaldi to Bruno Touschek September 15, 1952, Amaldi Archive, Sapienza University of Rome, Box 143, Folder 4, Subfolder 2.

He immediately became very active in the life of the Rome University Physics Institute, joining discussions and seminars and bringing with him the impressions from a life outside the restricted confines of Italy, the personal acquaintance with the great German and Austrian physicists, Sommerfeld, Pauli, Heisenberg. He became good friends with the Amaldi family and fully immersed himself in particle physics and in the debates about parity non conservation and invariance under various symmetries, in particular writing papers on chiral symmetry transformations [30, 31], and time reversal [32]. In Fig. 2 we show him during a Conference on Weak Interactions together with T.D. Lee and Wolfgang Pauli.[13]

At the same time, his work on accelerators during the war and in Glasgow during the planning and construction of the 300 MeV Glasgow synchrotron, made him curious and interested in the Frascati enterprise. Thus, when discussions started about building machines which could test quantum electrodynamics or find new physics, he was mentally prepared toward *realizing the impossible* and *thinking the unthinkable*, as Carlo Rubbia, who was also in Rome at the time, says in [15] and in [33].

By the fall of 1959 the first Italian electron syncrotron had reached a full regime of experimentation. With the Frascati machine, Italy had become competitive at an international level, especially with U.S. high energy physics. However, people were already speculating on ultra-high-energy accelerators beyond the Alternating Gradient Synchrotron at Brookhaven National Laboratory and the Proton Synchrotron (PS) at CERN, which were beginning to operate for physics. Touschek had followed the design and construction of the Italian machine, immediately writing a paper with Matthew Sands on the alignment errors in a strong-focusing synchrotron [34]. As he himself recalled years later, when the Italian synchrotron started operating "new preoccupations arose [. . .] it was felt that if Frascati wanted to keep abreast, something big and new had to be planned."[14] A series of seminars was held in Frascati National Laboratories in order to discuss proposals for experiments with the electron synchrotron, with the CERN Proton Synchrotron and aiming at developing new lines of research for entering in a new phase.[15] On February 17 1960, Touschek was invited to a meeting dedicated to the creation of a theoretical physics group. As he later wrote,[16] Touschek did not like this idea, "It smelled of what in Germany was known as the 'Haustheoretiker,' a domesticated animal, which sells itself and what little brain he has to an experimental institution to which it has to be 'useful' [. . .]. I was, however attracted by the possibility of learning how a big enterprise like Frascati worked [. . .]". Instead, he put forward an idea, which had been floating around in conferences [35] or discussions but had never been taken into serious consideration.[17]

[13] Touschek was in correspondence with Pauli until 1958, when Pauli died, and with T.D. Lee until the mid 1970s. A 1972 letter to T.D. Lee is reproduced in [14].

[14] B. Touschek, "A brief outline of the story of AdA", excerpts from a talk delivered by Touschek at the Accademia dei Lincei on May 24, 1974 (typescript, B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 92.5, p. 5).

[15] E. Amaldi to B. Touschek, November 21, 1959 and G. Salvini to B. Touschek, November 21, 1959 (B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 1, Folder 3).

[16] B. Touschek, AdA and ADONE are storage rings (incomplete typescript, B. Touschek Archive, Physics Department, Sapienza University of Rome, Series III, Section IV, Folder 11, 3.92.4, p. 7.)

[17] For example, on the occasion of the first international conference on high-energy accelerators held in Geneva in 1956, during the discussion following the Session "New ideas for accelerating machines" Giorgio Salvini commented as follows: "When we have 2 beams, one of positive particles and one of negative particles (travelling in opposite directions), can we expect extra focusing by the magnetic field of one beam acting on the other, or will the particles simply collapse?" [35].

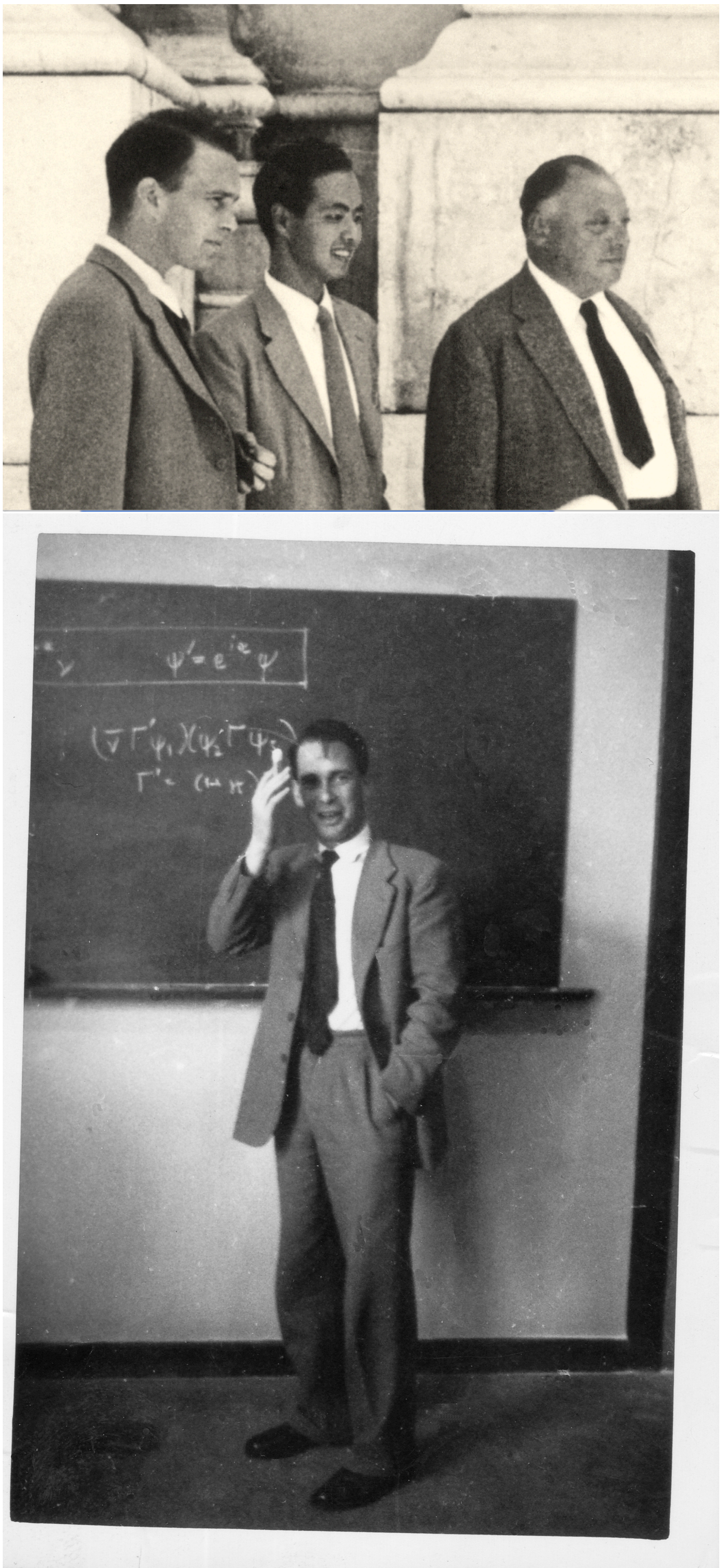


Fig. 2. At top Bruno Touschek with T.D. Lee and Wolfgang Pauli during the 1957 Padua-Venezia International Conference on Weak Interactions. On the bottom, Bruno Touschek in front of the blackboard in the late 1950s.

Touschek proposed to forget the electron synchrotron, which, with its 1100 MeV energy, was competitive with the most powerful of its kind in the world (the other two being at Cornell and at Caltech). To his colleagues, eager and waiting to start their planned experiments, he suggested transforming the newly built machine in a single ring for observing collisions between electrons and positrons.

The road which would lead to collide together positrons and electrons had started a few month earlier, during a seminar held in Rome by Pief Panofsky, the Director of Stanford High Energy Physics Laboratory (HEPL). At the time Gerry K. O'Neill, W. Carl Barber, Burton Richter, and Bernie Gittelman were discussing the construction of an electron-electron collider, following a proposal [36,37] by Jerry O'Neill of Princeton. The colliding-beam approach had been first proposed in 1956 by the collaboration Midwestern Universities Research Association and was based on the recently discovered fixed-field alternating gradient focusing. The construction of such a complex machine, which was expected to be capable of stacking intense beams of protons with interesting reaction rates, was never approved, but Donald Kerst, the leader of the Midwestern Universities Research Association group, who had built the first betatron, proposed to use *two* such machines with the beams colliding [38]. O'Neill was interested in proton-proton collisions at high center-of-mass energy [39], but thought that the goals of high intensity and colliding beams could be combined using an ordinary synchrotron to accelerate the particles, and then accumulating them in two rings which met tangentially, so that the two stored beams could be brought into collision. Stanford High Energy Physics Laboratory had an ideal source of electrons in the Mark III linear accelerator, and O'Neill's approach, with two electron storage rings with one common straight section, was implemented at Stanford starting from 1958. This approach was presented by O'Neill at CERN in June 1959 [40–42], in order to perform high-precision experiments and check the predictions of Quantum Electro-Dynamics.

In the fall of 1959, Pief Panofsky came to Italy and gave seminars in Frascati[18] and Rome. During the seminar in Rome, as remembered by Nicola Cabibbo [43] and Raoul Gatto [44], Panofsky presented and discussed the Stanford-Princeton electron-electron collider being built on the Stanford campus. Touschek's speculations emerged during discussions following the seminar. He was fascinated by the quantum properties of the vacuum which could be probed through the basic process of vacuum polarisation, and he immediately stressed the relevance of electron-positron reactions proceeding through a state of well-defined "minimal" quantum numbers. Touschek's outstanding idea was that, because of symmetry, opposite charges can be stored in one single ring, and made to collide head-on, provided that their masses are equal: "Bruno Touschek came up with the remark that an e^+e^- machine could be realized in a single ring, *because of the CTP theorem*" [23,43]. The discussions about a single ring are also remembered by Raoul Gatto [44], who was at a time a young assistant professor in Rome and who was to head the Frascati theory group for a while. He remembered that "There was a lot of discussion on technical issues on machine building. The question of a single ring instead of two was certainly discussed. I remember how Bruno kept insisting on CPT invariance, which would grant the same orbit for electrons and positrons inside the ring".[19]

Electron-electron collisions would allow to test the photon propagator in the space-like region; however, Raoul Gatto [44] recalled that "Answering to a question, Panofsky mentioned that, to test the electron (rather than the photon) propagator,

[18] The list of seminars held in Frascati during the period June 1959–1960, gives October 26th, 1959, as date of Panofski's seminar "On the two miles linear accelerator" (G.P. personal collection, courtesy of V. Valente).

[19] R. Gatto to L. Bonolis, December 2, 2003.

electron-positron collisions would have been suitable through observation of 2-photon annihilation, but that such a development could present additional technical difficulties and that for the moment it had been postponed." An electron-positron collider would have actually allowed to explore the time-like photon region as well as the electron propagator in the space-like region through the two-photon annihilation. However, in Touschek's views, the really exhilarating perspective would be the annihilation into hadrons. But one needed positrons to collide with electrons; thus, as Touschek remarked: "The challenge of course consists in having the first machine in which particles which do not naturally live in the world that surrounds us can be kept and conserved."[20] After the lively discussions following Panofsky's seminar, Touschek continued to reflect on the possibility of performing an experiment at the cutting edge of research in physics, and especially on the related difficulties. During his opening address at the already mentioned Frascati meeting of February 17, 1960, he immediately remarked he had thoroughly thought of what should be the "future goal", which might attract theoretical physicists at Frascati Laboratories: "an experiment aiming at studying electron-positron collisions." According to Touschek, such an experiment could be realized modifying the newly built electron synchrotron.[21] However, "This proposal was not very tactful in front of a meeting of people who had built the machine and were proud of it and others who had spent years in preparing their experiments and were eager to bring them to a conclusion," as he himself recalled years later.[22] At the end, Touschek stressed the importance of working at improving the intensity ("probably we need to inject with a linear accelerator, rather than with a Van de Graaff"), and listed three main items as preliminary to the realization of such a project: Intensity of the beam, Extraction of the beam, Acceleration of the positrons.

During the full discussion following Touschek's talk, Giorgio Ghigo, Machine Director of the electron synchrotron, observed that the synchrotron was not a machine which could be easily converted, and that it was "probably easier to construct an *ad hoc* 250 MeV machine, in order to carry out the experiment suggested by Touschek." At the end of the meeting, all participants agreed that Touschek's suggestion deserved a deeper study, and Giorgio Salvini, the director of Frascati Laboratories, stressed that they must go ahead with it.[23] Touschek immediately took up the challenge: the following day, on February 18, 1960, he started a new notebook which he entitled "SR", Storage Ring, where he explored the physics of the proposed e^+e^- storage ring.[24] We reproduce in Fig. 3 the first page of his first notebook.

In an incomplete manuscript in which he sketches some of the reasons which led him to propose building an electron-positron storage ring, Touschek stated that:

> The outstanding motive was my conviction that the plan was workable. As a theoretical physicist I had played with the symmetry properties of particle physics,

[20] B. Touschek, "A brief outline of the story of AdA", excerpts from a talk delivered by Touschek at the Accademia dei Lincei on May 24, 1974 (B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 92.5).
[21] Frascati, February 17, 1960, Report of the Meeting (Courtesy of F. Amman).
[22] B. Touschek, "A brief outline of the story of AdA", excerpts from a talk delivered by Touschek at the Accademia dei Lincei on May 24, 1974 (B. Touschek Archive, Physics Department, Rome University Sapienza, Box 11, Folder 92.5), p. 5.
[23] Frascati, February 17, 1960, Report of the Meeting. For an account of the early days of AdA and ADONE see [11].
[24] B. Touschek, "SR Notebook", B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 88. For a description of the SR-notebook content, see [13], pp. 28–35.

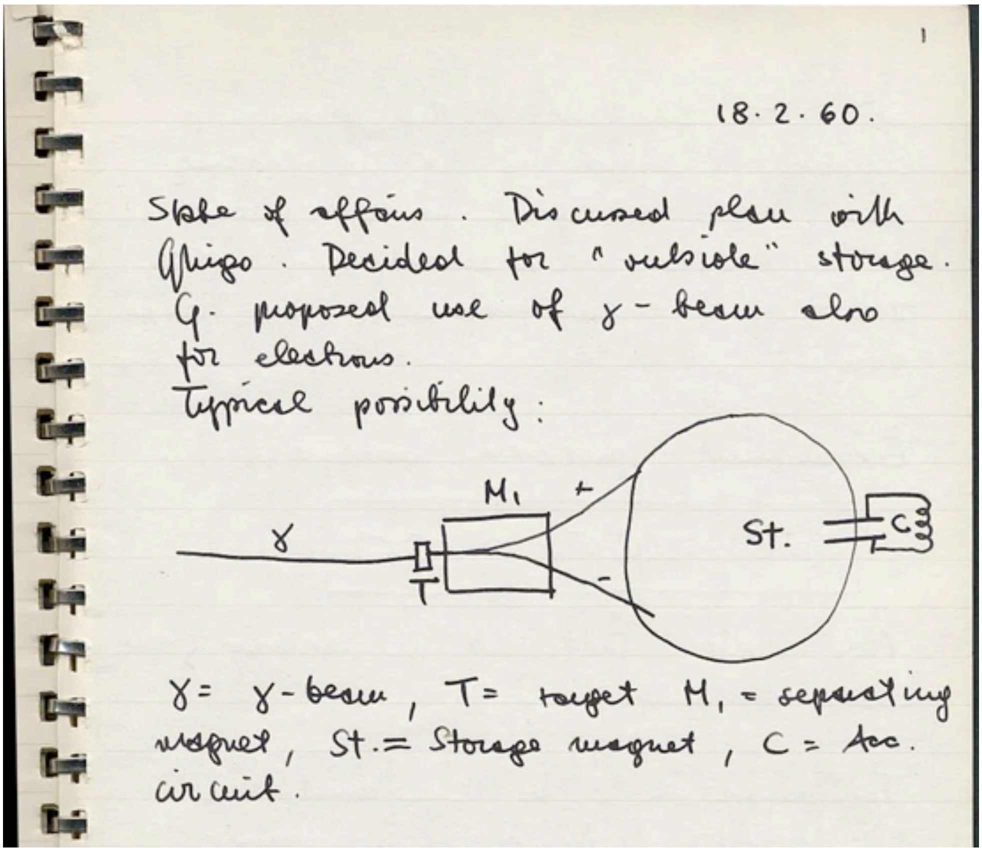


Fig. 3. First page of Bruno Touschek's first notebook, started on the day immediately following the Frascati meeting, where he had proposed to construct an electron-positron storage ring (Bruno Touschek Archive, Physics Department, Sapienza University of Rome).

which had become the centre of attention in 1957 through the discovery of the 'non conservation of parity' by Lee and Yang [. . .].
Another reason to prefer this type of effort to the more orthodox proposals of building a bigger and better machine (either for electrons or protons) is the following [. . .] the atomic nucleus is held together by strong interactions. They make very messy physics, theoretically, because there is no method of calculating them, perturbation methods breaking down, just because they are strong. [. . .]. Weak interactions — on the other hand — seemed hardly feasible, just because they are weak and the events they produce are therefore very rare — at least in the energy range, which we could hope to be available at Frascati by, say, 1964 [. . .]. We know that at least one stable strongly interacting particle – the proton – exists, that it interacts with the electromagnetic field [. . .]. The mere existence of the proton will therefore dictate a modification of pure electrodynamics and the proton itself can call into the fray all its strongly interacting friends. True electrodynamics can therefore not be indifferent to the existence of that part of the physical world which interacts strongly and noisly [. . .].
The third motive was more of a challenge than a reason: positrons unlike electrons are not constituents of ordinary matter. They have to be produced artificially [. . .].
The fourth argument was demagogic rather than physical[. . .]. Equal charges require two rings, opposite charges can be stored in one ring, provided that their masses

are equal. Italy being a poor country cannot afford an experiment which requires two rings. If we cannot even afford one ring we have the synchrotron which can be converted into one."[25]

By March 7 Touschek had thoroughly sketched the main lines of his idea, and he exposed a full project for a 250 MeV beam energy machine for positrons and electrons, with a 100 cm diameter, during an epoch-making seminar held in Frascati.[26] His colleagues were particularly impressed by "the extreme beauty of the 'time-like one-photon channel' dominating, to first order of QED, the production of final states," [45]. Striking everbody's imagination was the creative character of e^+e^- collisions providing a state of pure energy through a channel with well-defined quantum numbers, with no bias towards one form of matter or another and no complications from the "messy physics" of strong interactions in the final state. During the time between his first suggestion of February 17 and the March 7 seminar, he had been thinking about the physics which could be extracted from such machine, and the possibility to probe the "quantum vacuum and the frequencies at which it resonates" [12]. In a typescript document entitled "On the Storage Ring", which appears to have been prepared in view of the seminar, Touschek presented "a very sketchy proposal for the construction of a storage ring in Frascati."[27] In Fig. 4 we reproduce the beginning of this proposal. He recalled that it was from Widerøe that he had heard the first suggestion to use crossed beams, and pointed out the advantages of using beams consisting of electrons and positrons which disappear in the final state: "This means that much more information can be gained by much fewer events." At this stage Touschek defined a little better his project ("*I prefer to think of it as an experiment rather than as a machine* [...]" [our emphasis]) and proposed to study the reactions

$$e^+e^- \to 2\gamma \qquad (1)$$

$$e^+e^- \to \mu^+\mu^- \qquad (2)$$

$$e^+e^- \to \pi^+\pi^-(2\pi^0) \qquad (3)$$

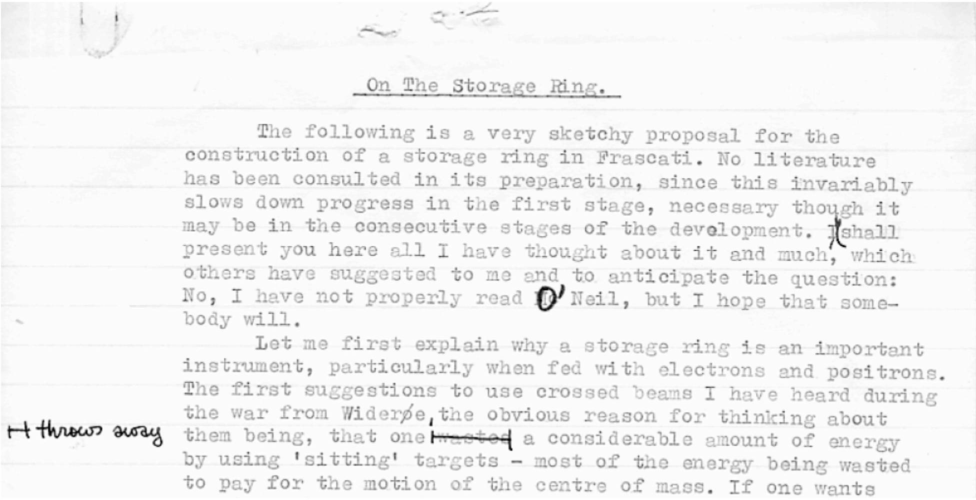
He proposed to use the first process as a "monitoring process", i.e. one with a well defined cross-section which would give rise to a calculable number of events, which he estimated should be at least one event per second and which could allow to then measure the cross-section for other processes. In these notes, he points out that "the first of the processes listed is [...] predominantly back-to-forward in the c.m. system and in these preferred directions no radiative corrections are expected". This comment throws light on what will become later his main preoccupation for ADONE experiments, i.e., higher order radiative corrections.

After calculating the cross-section for annihilation into photons as $\sigma = 6.3 \times 10^{-30}\ cm^2$, he estimated the number of events observed by such "luminosity" monitor, namely a monitor for events whose signal was given by two photons, writing the formula shown in Fig. 5, where $N_{1,2}$ is the number of particles circulating along a circular track of radius u, c is the speed of light, s is the length of the track where events can be observed and recorded, and q the cross-section of overlap between the electron and positron beam. η, explained Touschek, "is an enhancement factor, which

[25] B. Touschek, "A brief outline of the story of AdA", excerpts from a talk delivered by Touschek at the Accademia dei Lincei on May 24, 1974 (B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 3.92.5).

[26] In the previously mentioned list of seminars held in Frascati in the years 1959–1960, Touschek's seminar has the title "Anelli di cumulazione per l'urto elettrone positrone".

[27] B. Touschek, "On the Storage Ring", typescript, B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 3.86.1.

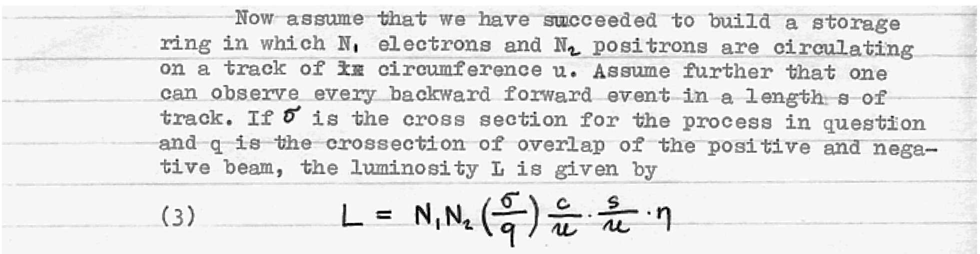


On The Storage Ring.

The following is a very sketchy proposal for the construction of a storage ring in Frascati. No literature has been consulted in its preparation, since this invariably slows down progress in the first stage, necessary though it may be in the consecutive stages of the development. I shall present you here all I have thought about it and much, which others have suggested to me and to anticipate the question: No, I have not properly read O'Neil, but I hope that somebody will.

Let me first explain why a storage ring is an important instrument, particularly when fed with electrons and positrons. The first suggestions to use crossed beams I have heard during the war from Widerøe, the obvious reason for thinking about them being, that one ~~wasted~~ a considerable amount of energy by using 'sitting' targets - most of the energy being wasted to pay for the motion of the centre of mass. If one wants

Fig. 4. The opening paragraph of the proposal for the construction of AdA by B. Touschek (B. Touschek Archive, Physics Department, Sapienza University of Rome).



Now assume that we have succeeded to build a storage ring in which N_1 electrons and N_2 positrons are circulating on a track of circumference u. Assume further that one can observe every backward forward event in a length s of track. If σ is the cross section for the process in question and q is the crossection of overlap of the positive and negative beam, the luminosity L is given by

(3) $$L = N_1 N_2 \left(\frac{\sigma}{q}\right) \frac{c}{u} \cdot \frac{s}{u} \cdot \eta$$

Fig. 5. The expression for the interaction rate, which Touschek called the luminosity, from the manuscript of the proposal for the construction of AdA by B. Touschek. Symbols as described in the text.

is due to the bunching of the beams and which can rise to 4 by a proper choice of the point of observation. L is measured in events/sec. If one can get q down to 1 cm^2, with $u = 300\ cm$ and $s = 10\ cm$ one gets, with $\eta = 4$ and $N_1 = N_2 = N$, $N \geq 10^{11}$, and this is the number of particles which one would want to circulate in the ring."

The number of events per second, which he had referred to as a "luminosity", had been his very first preoccupation. The term "luminosity" appears to have been used for the first time in Touschek's work, and was probably inspired by his proposal of a two photon state as the monitor for event rate. The interaction region, for instance, is referred to as "luminous region" in a discussion of the luminosity monitor at SPEAR [46]. Presently, the word "luminosity" is used to indicate the proportionality factor between the number of events and the cross-section. Previous estimates of the interaction rate in storage ring machines had been put forward by O'Neill in the context of the storage ring for protons, which O'Neill had proposed a few years earlier [39], and subsequently in unpublished reports on building the electron-electron Princeton-Stanford storage ring [36,37]. Touschek had certainly been inspired by O'Neill's work, although, as read from Fig, 4, he may not have been fully aware of the details.

In discussing the indicated processes, Touschek referred to a "recent paper of Cabibbo and Gatto".[28] Indeed, after Panofsky's seminar, discussions about the concrete possibility of e^+e^- physics were circulating in Rome and Frascati. Very soon, at the beginning of 1960, papers triggered by these discussions appeared. Among the young theoretical physicists in Rome University, Nicola Cabibbo and Francesco Calogero had been the first students to graduate with Bruno Touschek. The first paper to be submitted for publication in *The Physical Review Letters* was written by Laurie M. Brown and Calogero, and received on February 5. It calculated the effect of the pion form factor on the photon propagator [47]. The second one, received February 17 and published in the same number of *The Physical Review Letters*, was written by Nicola Cabibbo and Raoul Gatto [48].[29] The Gatto and Cabibbo paper was later completed with detailed calculations of the processes which could be explored at such machines, and became known in Frascati as *la bibbia* [the Bible] [49].

In the meantime, preliminary studies after Touschek's seminar did not show any insurmountable barriers. A week later, on March 14, the decision to go ahead with the project was taken and eight million lire were initially allocated for the proposed experimental device, later raised to twenty million (about thirty two thousand dollars at the time). It was decided that Touschek would be leader of the experiment, Giorgio Ghigo cooperating for the technical problems and Carlo Bernardini[30] for theoretical aspects.[31] Their competence has been established through the successful enterprise of building the Frascati electron synchrotron in record time. On March 16 Touschek and Ghigo prepared a first sketch of the program ahead, with a rough estimate of the working times, and an outline of the the main characteristics of the magnet, the vacuum chamber, and the radio frequency cavities. [32] The order for materials was placed on April 20. On April 3 Touschek had inaugurated what would become his "AdA logbook": the very first issue he discussed was "The vacuum".[33]

The sequence of events to follow is a measure of the enthusiasm and passion of all the scientists working on the project in Frascati at the time. On November 7 1960, "The Frascati storage ring", an article describing AdA, the first matter-antimatter collider, was received by *Il Nuovo Cimento* [1]: the small machine had a 65 cm radius and a beam energy of 250 MeV. On November 9, two days after submission of the paper, Touschek prepared a manuscript entitled "ADONE – a Draft proposal for a colliding beam experiment."[34] The proposal for the construction of a storage ring with beam energy of 1.5 GeV was presented at the annual meeting of the INFN in

[28] B. Touschek, "On the Storage Ring", typescript, Touschek Archive, University Sapienza, Rome, Box 11, Folder 3.86.1.

[29] Gatto recalled how they sent the paper to Physical Review Letters holding out "a very faint hope that the work would be accepted."R. Gatto to L. Bonolis, November 24, 2003.

[30] Carlo Bernardini, born in 1930, has been a prime collaborator of Bruno Touschek in the AdA enterprise. He is Professor Emeritus at Rome University Sapienza, has been Senator of the Italian Parlament, and chief Editor of "Sapere".

[31] The meeting was attended by F. Amman, C. Bernardini, N. Cabibbo, R. Gatto, G. Ghigo, G. Salvini and B. Touschek.

[32] The preliminary draft of this proposal was jotted down by Touschek (B. Touschek, "Proposta d'esperienza", two manuscript pages, Bruno Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 3.87.) and later fully elaborated by G. Ghigo into the final document dated March 22, 1960 (B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 3.80).

[33] B. Touschek, AdA Notebook, B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 11, Folder 3.89. The original document is still preserved by Elspeth Yonge Touschek.

[34] "ADONE – a draft proposal for a colliding beam experiment", typescript, B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 12, Folder 3.95.3.

Frascati and on January 27, 1961, F. Amman, C. Bernardini, R. Gatto, G. Ghigo and B. Touschek presented an Internal Laboratories Report with the title "Storage ring for electrons and positrons (ADONE)" [2].[35] In February 1961 a study group was formally set up with the task of preparing a first estimate of the feasibility and costs of such a project. Soon after, on February 27, 1961, *only one year* after Touschek's proposal, the first electrons had been accumulated in AdA using the Frascati electron synchrotron as an injector. In Fig. 6 we show a period photograph of AdA on the installation platform which allowed it to reach the level of the electron beam from the synchrotron. At right a photograph of Bruno Toushek during the construction of ADONE, in 1964.

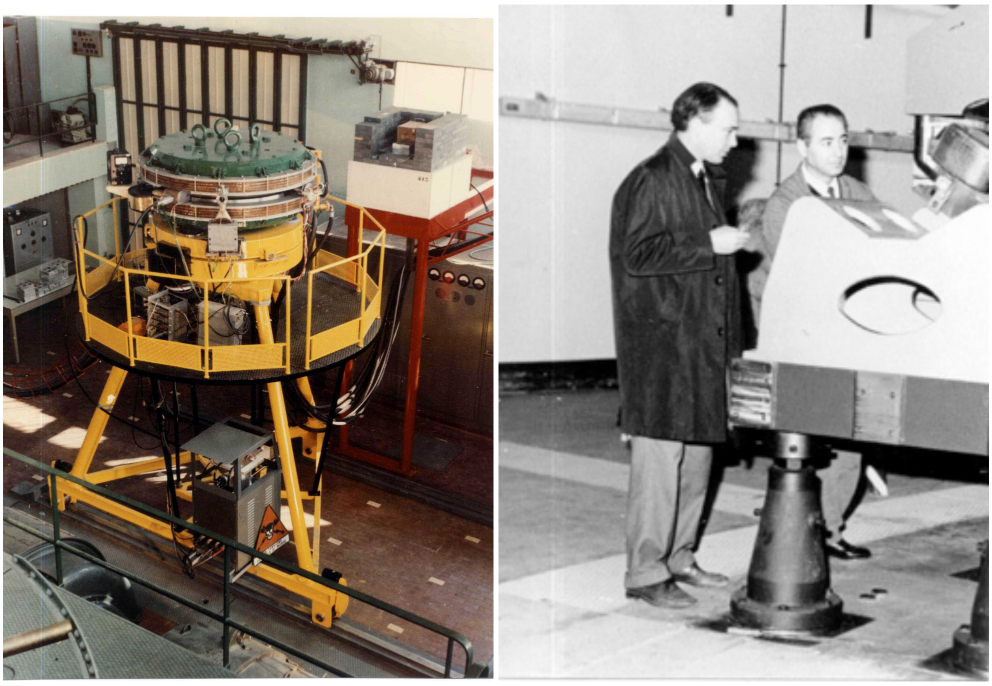


Fig. 6. The first electron-positron storage ring AdA, in 1961 (left). The synchrotron was used as an injector, until AdA was moved to Orsay in July 1962. Bruno Touschek in Sala Magneti (Magnet machine shop) during the construction of ADONE (right).

2.3 AdA at Orsay

AdA had been built by a small team of physicists and engineers led by Touschek, namely Carlo Bernardini, Gianfranco Corazza, Giorgio Ghigo and Giancarlo Sacerdoti (who took care of the magnet), and Mario Puglisi, Antonio Massarotti and Dino Fabiani helping to design the radio frequency cavity. Corazza, who had already taken care of the electron synchrotron vacuum chamber, was able to obtain an unprecedented vacuum in a volume as big (for the time) as AdA's doughnut. Ghigo was in charge of the overall assembly and operation of AdA.

[35] This report is reproduced as Appendix A in [14].

Actually the machine could not really work very well, because, in order to reach a luminosity sufficient to establish that electron-positron collisions had taken place, it needed a better injector. It thus happened that AdA was transferred to France, at LAL, the Laboratoire de l'Accelerateur Linéaire at Orsay, near Paris, where a high intensity linear accelerator (LINAC) was available. This transfer allowed to prove the feasibility of electron-positron collisions and launched the era of electron-positron physics.

It had all started with a visit to Frascati by Pierre Marin [50].[36] Pierre Marin, after a period spent at CERN, was trying to find his own research direction and was told that in Frascati "[il] se passait des choses qui intriguaient les esprits." In summer 1961,[37] together with George Charpak, Pierre Marin visited Frascati, and was soon caught by the enthusiasm of the Italian team about their machine, "un vrai bijoux". Marin's visit was quite successful and a collaboration was envisaged.[38] Letters were exchanged to allow two or three French scientists to come to Frascati. During a second visit, this time in early 1962, Marin became appraised of the disappointment about the lack of sufficient luminosity in AdA, which was due to the poor performance of the synchrotron as an injector. Pierre Marin recalls [50] that, as he started describing how good the linear accelerator in Orsay was, Touschek and Bernardini put forward the possibility of bringing AdA to Orsay and obtain a higher luminosity thanks to the high intensity LINAC. They proposed it to Marin and more letters were exchanged between the two laboratories.[39] According to the correspondence, by early April a decision about the date had been taken, and the transfer of AdA to Orsay was prepared.

[36] Pierre Marin, 1927-2002, played a principal role in the French effort to accelerator building in post-war Europe, including research with ACO, built at the Laboratoire de l'Accelerateur Lineaire, LAL in Orsay, near Paris.

[37] In [50] Marin dates his visit in August (1961), elsewhere in early September, while letters obtained courtesy of Jacques Haïssinski and exchanged between Frascati and LAL, indicate July 1961.

[38] On september 19, 1961 Marin prepared a report of his visit, where the possibility of bringing AdA to Orsay is already considered. In this report, agreed upon with Ruggero Querzoli, then in charge of Frascati experiments, Marin describes the future programs of AdA and ADONE. Listing one of AdA's objectives, Marin writes "S'il s'avérait qu'il ne se puisse être réalisé à Frascati, A.D.A. serait transporté á Orsay auprès de l'Accélérateur Linéaire." Copy of this report, which is preserved at Orsay, Archives of the Linear Accelerator Laboratory, was kindly provided by Jacques Haïssinski.

[39] Letters exchanged between Rome, Frascati and Orsay envisaged a collaboration between Orsay and Frascati which would include future experiments at ADONE. On December 22, 1961, André Blanc-Lapierre, the new LAL Director, wrote to Italo Federico Quercia, Director of Frascati Laboratories in order to organize a visit of two or three scientists from Orsay, where they were doing preliminary studies for a 1.3 GeV storage rings for electrons and positrons. On January 16 Amaldi (then Director of INFN) wrote to Blanc-Lapierre about the visit of the French scientists and about the importance of coordinating a future collaboration in the best possible way. As mentioned in a letter written by Blanc-Lapierre to Quercia on January 23, 1962, the date for the visit was fixed for February 5. The visiting group was formed by François Fer, Pierre Marin and Boris Milman. And indeed, on February 12, Fer thanked Touschek for "information and advices about storage rings" received during their stay in Frascati. On February 21 Touschek wrote to his collaborators as well as to Fernando Amman (who was leading the ADONE project) and to Amaldi, about a meeting dedicated to the Franco-Italian collaboration to be held the following Saturday. A new letter sent on April 4 by Blanc-Lapierre to Quercia, mentioned having met Carlo Bernardini and Fernando Amman in Geneva. During their conversation Bernardini had envisioned that AdA might be moved to Orsay next June (B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 1, Folder 4, and letters kindly provided by Jacques Haïssinski and preserved in LAL Archives).

André Blanc-Lapierre, the LAL Director, invited Touschek to give a seminar.[40] At the beginning of July, AdA was packed on a big truck, which would have to cross the Alps with a fully evacuated beam pipe, and batteries, lasting about three days, to power the vacuum pumps: at that time one needed months to reach the required pressures of order of 5×10^{-10} *torr* and one could not waste precious time obtaining the vacuum anew.[41] As the truck was ready to go, Touschek jumped in to try the driving, and immediately hit a lamp post, luckly without damage neither to himself nor to the truck and its precious cargo [12].

AdA owes its crossing the border between France and Italy to a number of high level diplomatic interventions. Touschek recalled the custom officer asking: "What's inside?", pointing at the doughnut. To which it was truthfully answered : "Nearly absolute vacuum."[42] But humor alone would not suffice to convince the border authorities, and a number of letters and telephone calls between France and Italy had to take place before AdA, with its high vacuum still intact, could enter France. Jacques Haïssinki, who would do his doctoral thesis [51] on the AdA results, writes [52] : "It took the intervention of Francis Perrin, then the Haut Commissaire l'energie Atomique, to get over this hurdle." Carlo Bernardini [53] remembers also the intervention from the Italian side, with Amaldi, in Rome, calling the Italian Ministry of Foreign Affairs, and, through this, the French authorities.

In early July 1962, AdA was in Orsay and, by August, installation was completed. The installation had its dramatic moments [52]. While being hauled by heavy crane in its place in the so called medium energy hall, AdA was almost smashed against a wall. It was Pierre Marin, alerted by yellings from the Italian group, who ran and pushed the buttons which averted the crash. Another time, one of the Cherenkov detectors, while being moved close to the AdA ring, tipped over and broke Pierre Marin's foot. None of this quenched the enthusiasm and drive of the Franco–Italian group, which was joined in the fall 1962 by Jacques Haïssinski. Once in Orsay, AdA started making collisions thanks to the linear accelerator and the dedication of the group. But soon, an unexpected effect appeared to limit the machine luminosity. What is now called *Touschek effect*, manifested itself through a progressive decrease in the beam life time while the number of stored particles increased. Still one of the effects which limit the beam life time in accelerators,[43] it was explained by Touschek as an intrabeam scattering effect, which changes the lepton momenta and throws the scattered particles off the designated orbit [54]. The effect was unexpected, also because of a wrong evaluation of the vertical beam size, assumed to be 1000 times larger in a multiple rather than single damped scattering regime; the wrong assumption was corrected by Carlo Bernardini, in an unpublished note [55], and fitted the Touschek calculation.

[40] André Blanc-Lapierre to B. Touschek, April 11, 1962 (B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 1, Folder 4).

[41] There is some confusion in the literature about the date of AdA's arrival in Orsay. In [12], a typo dates it in 1963, Pierre Marin talks of "début 1962", whereas Haïssinski [51] gives the date of summer 1962. As a matter of fact, on June 28, 1962 Touschek was writing to F. Perrin that "a second convoy [with AdA and the evacuated doughnut] will presumably leave Rome on the 4th of July and should arrive in Paris on the 7th." (B. Touschek Archive, Sapienza University of Rome, Box 1, Folder 4).

[42] Bruno Touschek, "Convegno Adone", manuscript dated May 5, 1974, prepared on the occasion of the meeting organized at the Accademia dei Lincei on May 24. Bruno Touschek Archive, Physics Department, Sapienza University of Rome, Box 8, Folder 61.

[43] L. Evans, The Large Hadron Collider, talk given during the *Bruno Touschek Memorial Lectures*, Frascati, November 30th, 2010.

2.4 AdA's legacy

AdA showed the feasibility of electron-positron collisions [56], and opened the way to the machines which would discover new fundamental particles and bring the experimental confirmation of the Standard Model. Soon after the proposal for AdA appeared, proposals to build more powerful colliders, in the USA and Europe, were put forward, with higher energy and higher luminosity, among them ACO in France [50], and SPEAR [10,57,58] in the USA.[44] In Italy the construction of ADONE, proposed as early as January 1961 [2], was under way by the end of the year: orders, financed by the Comitato Nazionale per l'Energia Nucleare (CNEN)[45] were issued for various parts, and construction was started in 1963 [59]. Similar efforts took place also in the Soviet Union, where Gersch Budker[46] and his collaborators had been active since the midfifties in electron-electron colliders, and later in electron-positron collisions. Because of the internal political situation of that period, early records of Russian efforts in electron-positron studies are very scarce. Their work became partly known to scientists from outside the Soviet Union in 1963, in occasion of the Dubna Conference on High Energy Accelerators, where Budker gave a talk in Russian on the activity on particle colliders which had taken place in the Soviet Union since 1956. According to [50], none of the foreign scientists present to his talk understood Russian, however, and, although there was a simultaneous translation,[47] not much of his presentation was understood. From the Conference Proceedings [60], published in Russian in 1964, one can see that Budker and his collaborators indicated and described three types of activity: electron-electron, electron-positron and proton-proton collisions. After the conference, a few foreign visitors were invited to see the newly established Institute of Nuclear Physics (now Budker Institute of Nuclear Physics) of the Siberian Division of the USSR Academy of Sciences in Novosibirsk, three thousand kilometers to the East of Moscow. Pierre Marin [50] remembers the astonishment in seeing VEPPII, the electron-positron accelerator with an energy of 700 MeV, in such an advanced stage of preparation to indicate that work on it must have been taking place for quite some time. For electron-positron collisions, nothing of this had appeared before the Conference. After the Conference Proceedings arrived in 1964, a French translation of Budker's talk was commissioned in Orsay, as well as an English translation exists [61]. The French translation remained practically ignored until chance saved it from destruction in the year 2000.[48] In these Proceedings, Budker dates the start of electron-positron work in late 1958, but this appears unlikely, as also discussed in

[44] SPEAR was completed in 1972. See also [57] for a source book on the development of colliders, and [58] for an account on the rise of colliding beams made by Burton Richter, one of the protagonists of the field. It is however to be mentioned that Richter, even if giving due credit to the importance of ADONE for the development of new physics with colliders, still made the following sharp statement about AdA on p. 269 of his essay: "In my opinion, AdA was a scientific curiosity that contributed little of any significance to the development of colliding beams (there is one exception; a beam-loss mechanism now called the Touschek effect was discovered) [...]". This sentence sounds too dismissive of the influence of AdA's work, in light of other assessments, as, for instance, in [50]. For discussion on this topic see [13], especially p. 50.

[45] The Frascati Laboratories, operational in 1957, were staffed and partly financed by INFN, with CNEN owning the grounds and financing the major projects.

[46] G.I. Budker was called Andreij Mikhailovic by his friends, as for instance in [53].

[47] Courtesy of A. Skrinsky, INP Director since 1977.

[48] A copy of the French translation of Budker's talk was sent by Pierre Marin to Carlo Bernardini in a letter dated December 26, 2000. In this letter Marin also notices that the literature quoted in these Proceedings only refers to electron-electron studies.

[7].[49] Presently, Russian contemporary sources would rather place the start not earlier than 1959. Since then, a number of contributions have appeared which put forward some dates in the Russian development of electron-positron collisions [62,63]. In [63], the Russian theorist Vladimir Baier vividly recalled how the appearance in 1960 of the *Nuovo Cimento* paper by the Frascati group [1] strengthened their resolve to build an electron-positron collider. In this recollection he writes to have started working on electron-positron collisions at the end of October 1959.[50] Even if the theoretical work started as early as in the case of the Frascati group, the Russian progress in building a working accelerator was delayed[51] by moving from the Kurchatov Institute in Moscow to the Novosibirsk site and by the secrecy surrounding its construction. In addition, serious technical problems with the vacuum slowed down quite a bit the work of the Siberian team.[52]

The legacy of Touschek's work appears very clearly from [63], where the impact of the successful experimentation in Orsay, which had been followed by the ACO and ADONE projects, and the discovery of the *Touschek effect*, are described as clear signs that electron-positron collisions had become "very respectable" and a race to obtain useful physics results could now start.

The above is a short and limited account of Touschek's work on AdA and how the road which led to the discovery of the J/Ψ and to the establishment of the Standard model had been opened. We shall now describe Bruno Touschek's life prior to his arrival in Italy and the dramatic experiences and scientific exchanges which brought him to the Physics Institute of Rome University and to the construction of AdA.

3 Touschek's life prior to arrival in Italy

3.1 Early years: 1938 – 1941

Bruno Touschek was born in Vienna, on February 3rd 1921 from Franz Xaver Touschek,[53] an officer in the Austrian army, and Camilla Weltmann, who belonged to a Viennese Jewish family prominent in artistic and intellectual circles like the Vienna Secession and the Wiener Werkstätte. Camilla Weltmann died when Bruno was ten years old, but he kept frequent and intense relations with his maternal family, in particular with his aunt Adele, called Ada, who lived in Italy, married to an Italian businessman, and had a villa on the Alban hills southeast of Rome. Early letters to his parents (the father had remarried) testify to his love for Italy and Rome in particular. In 1938, however, everything changed forever for the Vienna Jewish community. The Nuremberg Laws of September 15, 1935, had established that a person was considered Jewish if at least three grandparents were of Jewish religion. When on 12 March 1938 German troops entered Austria, German laws became also Austrian laws. With

[49] According to Amaldi ([7], footnote 114, p. 78), "it appears reasonable to conclude that the activity on e^+e^- storage rings was started [in Soviet Union] after 1961 and no document is known which proves the contrary."
[50] Baier describes a discussion with Budker on October 28th, 1959, during which he first proposed physics with electron-positron collisions, and writes that he started working on it on the following day.
[51] Data taking at VEPPII started in 1966 [63].
[52] Such problems were well known, according to Carlo Bernardini. Private communication to the authors.
[53] The family name Touschek comes from Moravia, which, with capital Brno, belonged to Czech country and Slovakia and now belongs to Czech state. The name is also current in the southern part called Sudety.

annexation to Germany, political and racial criteria were quickly applied, and Jewish students were soon not allowed anymore to attend classes in the Gymnasiums.

Only two of Touschek's grandparents were of Jewish religion, still, as Touschek was ready to start the last year of high school (gymnasium) in the fall of 1938, he was told that he could not attend his classes anymore nor take the final *(matura)* examination, the obligatory passage to the university, together with his friends and schoolmates. He had to abandon the Piaristen Gymnasium. However, he was still able to obtain his diploma, by registering for the exam as a private student, and, in February 1939, he graduated from the Vienna Schottengymnasium. The exam had been anticipated, because the Austrian authorities wanted to have as many young officers as possible ready for the war [7,8].[54]

After passing the exam, as the custom was, Bruno went to Rome, in Italy, visiting his aunt Adele, called Ada, for the vacation traditionally following the end of the high school years. From letters exchanged with his father, we learn that he was waiting for a visa which would allow him to go to Great Britain and study Chemistry in Manchester.[55] At the same time, he also considered studying engineering in Rome, and started attending some classes, following "with enthusiasm" the course of Mathematical Analysis taught by the mathematician Francesco Severi. But after his return to Vienna for a family vacation in Summer 1939, everything changed.

In September 1939 World War II started with Hitler's invasion of Poland. Bruno's plans of studying abroad were completely upset, and in October he enrolled to study physics and mathematics in the University of Vienna, where he attended ten courses and passed the exams, (mostly in Mathematics and Theoretical Physics).[56]

In May 1940, as he was beginning to emerge as a brilliant student, university life also closed for him "for racial-political reasons".[57] He continued his studies at home reading books loaned to him by Paul Urban, then a young assistant professor at University of Vienna.[58] In a letter written to Amaldi after Touschek's death, Urban recalls how he would invite Bruno Touschek and other students to his house, where they could study and, occasionally, also have meals prepared by Urban's mother.[59] It

[54] We note here that in [7,8] Bruno Touschek is said to have received his *matura* in February 1938, but this makes the chronology very confused: it is unlikely that he could have been expelled from the Lyceum until the *Anschluss* took place, and this establishes that he must have obtained his *matura* in 1939 as confirmed by a document and also stated in Bruno Touschek's Curriculum Vitae (CV) still preserved by Touschek's wife Elspeth Yonge Touschek.

[55] Touschek wrote very often to his parents (his father had remarried after Bruno's mother's death) and gave many details of his everyday life. The whole correspondence, which spans between 1939 and 1971, is still preserved by Touschek's wife Elspeth Yonge Touschek.

[56] In his CV, he says to have attended and taken exams for ten courses, among them Physics Laboratory I and II, Differential Equations and Exercises, Mathematical Seminar, Rational Mechanics, Theory of Functions and Exercises, Introduction to Theoretical Physics, Statistical Theory of Heat, Thermodynamics ("Curriculum Vitae del Prof. Bruno Touschek", B. Touschek personal papers preserved by Elspeth Yonge Touschek).

[57] "Breve Curriculum Vitae del prof. Bruno Touschek", Amaldi Archive, Physics Department, Sapienza University of Rome, Box 524, Folder 4.

[58] Paul Urban, who had obtained his Ph.D. in physics and mathematics at the University of Vienna in 1935, was Hans Thirring's assistant at the Institut für Theoretische Physik of the University of Vienna. Urban later became Professor of Theoretical Physics at University of Graz and, in 1962, founded the Schladming Winter School of Theoretical Physics.

[59] Paul Urban to Edoardo Amaldi, June 3, 1980, Amaldi Archive, Sapienza University of Rome, Box 524, Folder 4, Subfolder 4. Reconstruction of this period is mainly based on documents and correspondence preserved in Box 524 of the just mentioned source, and in Touschek's correspondence with his parents and with Sommerfeld.

is during this period that, with Urban's help, he studied the first volume of Arnold Sommerfeld's treatise *Atombau und Spektrallinien* [64].[60] Having found some small errors he wrote a letter to Sommerfeld encouraged by Edmund Hlawka, a professor of Mathematics at the University of Vienna, who later became worldwide known for his works in number theory. According to Urban, they always discussed with Hlawka difficult issues.[61] Sommerfeld suggested him to read the second volume as well [65]. Later Touschek recalled how he had learned quantum theory from the second volume of Sommerfeld's treatise and how he had also "tried Dirac's famous book", both of which "lean heavily on wave mechanics."[62]

But life for Urban's protégés soon became difficult, because Urban's principal, Theodor Sexl, was continuously requested by the University to take measures concerning students not complying with the racial laws. At last, to help Touschek to continue his studies *incognito* away from Vienna, Urban decided to put him in contact with influential physicists of the time from whom he hoped to have some help in finding a position for Touschek in Germany. The occasion arose from a seminar on the tunnel effect, on which Urban had worked at that time, and which he was going to present in Munich in the presence of Sommerfeld and other prominent physicists.[63]

Apart from his theoretical works on the quantum theory of the atomic structure, Sommerfeld had given a fundamental contribution to the new physics in training more than a generation of Germany's best theoretical physicists. His students included Wolfgang Pauli, Werner Heisenberg, Hans Bethe, Peter Debye, Walter Heitler, Isidor Rabi, Rudolf Peierls, Gregor Wentzel; many of them were to become Nobel Prize winners. In 1928, nearly one-third of all full professors of theoretical physics in the German-speaking world were Sommerfelds pupils. Sommerfeld had always openly supported Einstein and his physics when the latter had been attacked. After his retirement in 1935, he had held his position during the long selection process for his successor, which ended in December 1939, when at last Wilhelm Müller was appointed to Sommerfeld's chair of theoretical physics [66].[64]

At the time of Urban and Touschek's visit, Sommerfeld had found hospitality in Klaus Clusius' Institute of Chemical Physics, where he ran a small seminar followed by friends and admirers. Urban held his seminar on November 24, 1941, and brought Touschek with him in order to ask Sommerfeld's support and help. A few days later, on December 2, 1941, Urban wrote to Sommerfeld, sending greetings for his birthday

[60] Since its appearance in 1919 and up to the beginning of 1940s, the first volume of Sommerfeld's treatise underwent several editions (1919, 1921, 1922, 1924, 1931), and we do not know which one Touschek used.

[61] P. Urban to E. Amaldi, June 3 and September 16, 1980, Amaldi Archive, Sapienza University of Rome, Box 524, Folder 4, Subfolder 4. Information on this episode is contained in the first biographical notes taken by Amaldi on February 28, 1978 and based on Touschek's personal recollections (E. Amaldi, Typescript with handwritten notes, Amaldi Archive, Physics Department, Sapienza University of Rome, Box 524, Folder 6). However, the first letters written by Touschek to Sommerfeld are apparently missing, so that we are not able to reconstruct the dates of the first contacts between Touschek and Sommerfeld.

[62] B. Touschek, "Remarks on the influence of Heisenberg on physicists", undated manuscript (Bruno Touschek's personal papers preserved by Elspeth Yonge Touschek).

[63] This issue is mentioned in a letter written by A. Sommerfeld to P. Urban, on October 17, 1941, a copy of which was sent by Urban to Amaldi with a letter where he told the whole story (P. Urban to E. Amaldi, June 6, 1980, Amaldi Archive, Sapienza University of Rome, Box 524, Folder 4, Subfolder 4).

[64] Sommerfeld had repeatedly suggested Heisenberg as his favorite successor, and the final choice was much criticized, also because Müller was not a theoretical physicist, and had not even published in a physics journal, but was a supporter of Deutsche Physik.

and thanking for the hospitality.[65] The latter answered immediately and mentioned the possibility of a position for Touschek in Hamburg, suggesting that "he could attend the good courses given by Prof. Lenz and Harteck."[66] On December 20 Touschek thanked Sommerfeld for "his friendly handling of the Hamburg matter"; at the same time he discussed some aspects of the scattering theory, clearly referring to Sommerfeld's *Atombau*, and quoting the existing literature.[67] We know what Sommerfeld answered to Touschek's letter of December 20 thanks to the stenographic text that he must have dictated to his secretary and which can be found at the end of the letter. The opening lines confirm that Touschek had already written before that date: "After the commendable addenda of your letter of Dec. 20, everything seems clear [. . .]" ("Nach den dankenswerten Ergänzungen Ihres Briefes vom 20ten Dec. scheint alles klar").[68]

Touschek wrote again at the end of the year reporting on his calculations and telling that he had found only "a few errors (except IV) [. . .]".[69] All these discussions were often related to the new edition of *Atombau* which Sommerfeld was preparing and which appeared in 1944. Sommerfeld thanked Touschek and Urban at the end of the preface [65]. However, Urban was rather annoyed because Touschek, without mentioning the matter in advance, had taken the initiative to write Sommerfeld about his own ideas on issues previously discussed with Urban himself. In a letter written by Urban to Sommerfeld on January 4, 1942,[70] the former complained about Touschek's behavior and distanced himself from any future opinion his pupil might express about scientific questions of common interest. In the opening lines of his answer of January 9, Sommerfeld stressed how sorry he was that he had someway been responsible for the misunderstanding. He added that, he himself had written to Touschek with the aim of proposing him the job in Hamburg ("manufacturer seeks assistants"). He remarked that, if in this occasion Touschek had also written about the scattering problem, was not to be considered "as an arbitrariness or even a lack of sincerity" towards Urban, and in fact, he added, he had sent greetings for him and for Sexl. He encouraged Urban to get over his distrust and made clear that he would be very pleased if Urban

[65] P. Urban to A. Sommerfeld, December 2, 1941. Deutsches Museum Archive, NL 89,017.
[66] See A. Sommerfeld to P. Urban, December 2, 1941. Copy of the letter was sent by Urban to Edoardo Amaldi, Amaldi Archive, Physics Department, Sapienza University of Rome, Box 524 Folder 4, Subfolder 4.
[67] B. Touschek to A. Sommerfeld, December 20, 1941, Deutsches Museum Archive, HS 1977-28/A,343. This is the first of the letters written by Touschek preserved in Sommerfeld's correspondence, but there are clear hints in the text showing that he must have written at least once or even twice before the letter of December 20. Unfortunately, as far as we know, these letters got lost. No letter written by Sommerfeld is preserved among Touschek's papers.
[68] Sommerfeld continued remarking that "[. . .] after having worked so deep into this direct approximation method, you should give a positive turn [. . .]" (" [. . .] so sollten Sie, nachdem Sie sich so tief in diese direkte Annährungsmethode eingearbeitet haben, die positive Wendung geben"). Here Sommerfeld referred to Touschek's observation that "the development of α_f was not granted in the first approximation, and asked him to discover why Sexl and Urban's formula showed a better agreement with observations if compared with Mott's shortest version [. . .]". The transcription of Sommerfeld's answer is attached to the letter preserved at the Deutsches Museum Archive, NL 089,015. Up to now this is the only evidence we have for Sommerfeld's answers to Touschek's letters.
[69] B. Touschek to A. Sommerfeld, December 31, 1941. Deutsches Museum Archive, HS 1977-28/A,343.
[70] P. Urban to A. Sommerfeld, January 4, 1942. Deutsches Museum Archive, HS 1977-28/A,343.

would let Touschek continue to work with him on those tricky issues. He closed the letter quoting a sentence from the Bible about the necessity of loving each other.[71]

Sommerfeld's interest and benevolence towards Touschek should not surprise. A great scientist and a great teacher, Sommerfeld could only view with favor a brilliant student like Bruno Touschek, eager to continue his studies and so interested in theoretical physics. Indeed, Sommerfeld's wider interest in helping the young Austrian, is made clear by a letter he wrote in that same period, early autumn of 1941, to the "State (Reich) Minister" ("Staatsminister") Friedrich Schmidt-Ott about the state of physics research in Germany, and about the necessity of concentrating funds on a few relevant research projects. Sommerfeld's main worry was the state of theoretical physics: "The difficulty is only to find adequately trained young theoreticians in Germany, after the awful bleeding that the previously flourishing theoretical physics has experienced during the last years. The state of things is really desolate. Planck's chair is still unoccupied. On my chair a man was called, merely for Party's interests, who never had any involvement with modern physics and who does not show any interest in it."[72]

This unpublished correspondence provides an insight on Sommerfeld's role in helping Touschek to find a work in Hamburg, which would allow him to earn his living. At the same time, he was entrusting him to physicists who would not betray him and would help him to continue his studies. On January 12 Touschek announced to Sommerfeld that he had been very happy in receiving "a friendly letter from Dr. Jobst" and that he had begun to read more experimental books on electronic devices (Brüche, Recknagel).[73]

3.2 Clandestinity in Germany. 1942-1944

During this period, Bruno Touschek put the basis of his knowledge of the physics of accelerators, which brought him later to construct AdA. He learned about accelerators through his encounter with the Norwegian engineer Rolf Widerøe, who built the first European betatron [9]. The story of Touschek's encounter with Widerøe and their collaboration in the construction of the betatron belongs to the history of accelerators and will be briefly described in this section.

In early 1942, Touschek started his new life in Germany. On February 26, 1942, Touschek was writing to his parents from Munich: "Sommerfeld has recommended me to Prof. Harteck, Lenz and Möller in Hamburg, who can help me to work without impediments in the local university".[74]

By March 4 Touschek, writing from the Hotel Reichshof in Hamburg, was looking for an apartment. He also mentioned that Sommerfeld had asked him to make some

[71] A. Sommerfeld to P. Urban, January 9, 1942. Deutsches Museum Archive, NL 089,015.

[72] A. Sommerfeld to F. Schmidt-Ott, September 24, 1941. Deutsches Museum Archive, NL 089,015.

[73] B. Touschek to A. Sommerfeld, January 12, 1942, Deutsches Museum Archive, NL 089,015. As far as we know this is the last letter Touschek wrote to Sommerfeld before the end of the war. Günther Jobst worked for the Allgemeine Deutsche Philips Industrie which had been founded in Berlin with the name Philips Deutschland in 1926, and had very soon acquired in Hamburg the C.H.F. Müller company, known as Röntgenmüller.

[74] Paul Harteck, a well known Austrian born chemical physicist, was director of the Department of Physical Chemistry. Wilhelm Lenz had been Sommerfeld's student as well as his assistant in Munich. From 1921 he was at University of Hamburg as Ordinarius Professor of Theoretical Physics and Director of the Institute of Theoretical Physics. In Hamburg Lenz had the collaboration of Wolfgang Pauli, who was his assistant, and Otto Stern, so that the Physics Institute became an international center for nuclear physics.

calculations and to control corrections to the Italian edition of his *Atombau*.[75] In Hamburg, Touschek found the possibility of continuing his studies. From various sources and so far unpublished letters to his parents,[76] we know that during 1942 Touschek attended classes at the University of Hamburg as an auditor not regularly registered, and studied theoretical physics under the guide of Wilhelm Lenz who held a course on relativity.[77]

Other courses were taught by J. Hans D. Jensen, who had been Lenz's student.[78] Another prominent physicist, Otto Stern, when Touschek arrived in Hamburg, was not teaching there anymore. Jensen and Lenz, being related to Sommerfeld, could be trusted in supporting Touschek in his semi-clandestine life in Germany, where his Jewish origin was not as easily detectable as it had been in Vienna.

To earn his living in Hamburg, Touschek worked at Studiengesellschaft für Elektrongeräte, a society associated to Philips, with the aim of developing an electronic valve, a precursor of the "klystron". Sommerfeld himself had got him this job, through Günther Jobst, who had been Sommerfeld's student after World War I.[79]

Toward the end of 1942 Touschek moved to Berlin, where started to work at a small electronic devices firm, (Löwe) Opta Radio, where he had the task of developing oscillographic valves for the radar,[80] a pivotal event in Touschek's life, which led him to the encounter with Widerøe and accelerator physics, as we shall now narrate.

Bruno Touschek was introduced to the Opta Radio by a young woman he had met on the train to Berlin and who worked there with Karl A. Egerer, who was also editor-in-chief of the scientific magazine *Archive für Elektrotechnik*. When in Berlin, he tried to continue his studies, and followed some lessons at the University. Together with Göttingen and Munich, Berlin was one of the three prominent centers where modern physics had been developed since the beginning of the 20th century. It was considered the citadel of German physics, where Max Planck had founded quantum theory in 1900. Von Laue, who had been his pupil, held there an extraordinary (ausserordentlicher) professorship in theoretical physics and had always taken public

[75] The Italian edition never appeared, most probably because of problems connected with the difficult situation due to the war.

[76] In addition to the letters written to his parents from 1941 until early spring 1945, other direct sources of information for this period of Touschek's life are Widerøe's biography [9], the recollections written by Rolf Widerøe to Edoardo Amaldi in 1980 and some notes on Touschek's personal remembrances taken by Amaldi when the latter was already very ill in Switzerland. Other informations are drawn from different versions of Touschek's Curriculum Vitae preserved in Touschek's and Amaldi's papers at the Physics Department of Rome University Sapienza, as well as in personal papers kept by his wife Elspeth Yonge Touschek.

[77] Some physicists remembered how specific directives had forbidden mentioning Einstein's name in lectures and even in published articles. However universities did not cease to teach relativity theory, even if the description "the electrodynamics of moving bodies" was generally used (see [66], pp. 169–170).

[78] J. Hans D. Jensen had received his doctorate at the University of Hamburg under Wilhelm Lenz, and since 1937 he was Privatdozent (unpaid lecturer) at the University of Hamburg, where he collaborated with Paul Harteck.

[79] B. Touschek to A. Sommerfeld, Wien, January 12, 1942, Sommerfeld Archive Deutsches Museum HS 1977-28/A,343; "Curriculum Vitae del prof. Bruno Touschek" and "Curriculum Vitae" (Bruno Touschek personal papers); "Breve Curriculum Vitae del prof. Bruno Touschek", Amaldi Archive, Sapienza University, Rome, Box 524, Folder 4, Subfolder 4. See also correspondence of the period.

[80] See text of a patent with the title "Einrichtung zur Bestimmung der Geschwindigkeit eines Geschosses"; discoverer: Touschek, Berlin, and presented by Opta Radio Aktiengesellschaft (B. Touschek Archive, Physics Department, Sapienza University of Rome, Box 3, Folder 5).

stand against the government dismissal politics. Touschek attended his lectures on the theory of superconductivity, on which the latter had made prominent contributions.

It was in Berlin that Bruno Touschek's life crossed path with Rolf Widerøe's. At first Touschek came to know Widerøe because of the work with Dr. Egerer in the editorial department at *Arkiv für Electrotechnik*, to which Widerøe had submitted an article on the betatron. Later they met in Hamburg, and started collaborating on the construction of the first European betatron. From their encounter, the road to electron-positron colliders started. In his autobiography Widerøe , races the birth of storage rings to the summer 1943 when he was in Norway observing clouds collide in the sky, and relates later discussions with Touschek about the possibility of head-on-collisions between oppositely charged particles. Such discussions about head-on-collision where also remembered by Touschek in his first notes about the building of AdA, as one can read in Fig. 4. Widerøe's photograph is shown in fig. 7.

In 1942, Rolf Widerøe was living in Oslo, working for Norsk Elektrisk og Brown Boveri (NEBB), and his article, submitted on September 15, 1942, and subsequently published in 1943 [67], discussed Kerst's recent results on the construction of a 2.3 MeV betatron and presented new ideas for the future as well as a design for a 100 MeV betatron.

Fig. 7. Rolf Widerøe at 18, from [9].

Widerøe was the author of a seminal paper where he had presented the design of the first functioning linear accelerator and described the Strahlentransformator, a new device which later became known as betatron [68]. The article was the result of his thesis work entitled "Über ein neues Prinzip zur Herstellung hoher Spannungen".[81] Before the war, work on development of the betatron has been actively pursued in the USA, where D.W. Kerst and R. Serber had then operated the first successful betatron at the University of Illinois and the results had been published in *The Physical Review* [69]. Almost by chance [9], because all American journals were banned in Germany occupied Norway, Widerøe had come to know of Kerst's article and found that, in this article, Kerst had referred to the work of his thesis.

[81] In his article Widerøe described the principle of alternating current-based multiple acceleration which he had used for constructing the worlds first linear accelerator. At the same time, he presented the first comprehensive description of the principles for the betatron, including the fundamental 2:1 equation $\frac{d\bar{B}_j}{dt} = 2\frac{dB_f}{dt}$ for the space-averaged field strength in the core and the guiding field at the orbit, that permits simultaneous acceleration and maintenance of the orbit at a constant radius and which later became known as "the Widerøe relation." Some years later Ernest O. Lawrence found a copy of Widerøe's thesis on the linear accelerator in a library and drew from it the idea to build the world's first cyclotron in 1939 introducing a fixed magnetic field to obtain a circular path for the accelerated particles.

Stimulated by Kerst's article, Widerøe had then decided to write his own proposal for the construction of new betatrons with higher energies and intensities and in the Autumn of 1942 submitted to the *Archiv für Elektrotechnik* an article where he discussed a project for a 100 MeV betatron

Early in 1943, Touschek came to know about Widerøe's proposal and wrote to him.[82] Thus a life-long friendship and collaboration started between these two men, brought together by different personal adverse circumstances to work on particle accelerators.

The article must have also reached the attention of the German Air Force which had been interested in financing the betatron to explore this technology and obtain highly focused high intensity X-rays bundles (that they hoped coud be used to kill the pilots of enemy aircraft), something often referred to as "death-rays".[83] Thus it happened that, one day, as Widerøe recounts in his autobiography [9], in March or April 1943, he was approached in Oslo by some German Air Force officers, and asked to go with them to Berlin for a matter of importance to his brother Viggo Widerøe. At that time, Widerøe's brother Viggo, a pioneer of Norwegian aviation, had been arrested in Norway for activities against the Nazi regime and sentenced to 10 years hard labour in concentration camps in Germany. The whole family was obviously concerned about his well being. In order to secure help for his brother, Widerøe, initially unaware of the military uses envisaged by the German authorities, accepted to cooperate in the development of betatron technology. The project, which was financed by the Reichsluftfahrtministerium (RLM), the Ministry of Aviation of the Reich, was given high priority and adequate resources especially with regard to funding and staff [70].

After reading Widerøe's article, Bruno Touschek wrote to him [7] about some mistakes he thought were contained in the relativistic treatment of the stability of the orbits and a correspondence ensued, which has not been retrieved. We know however that, on June 17th 1943, he was writing to his parents about a meeting at RLM with Widerøe (whom he calls "Mein Norweger" and does not mention by name probably for reasons of secrecy) concerning some points of physics. It appears that Touschek must have convinced Widerøe about his ideas, because he wrote that something would be changed in the project and that he hoped to write two or three papers on the subject of their discussion, part of which would probably be published as RLM Internal Reports owing to secrecy problems.[84] From the above, it would appear that a considerable amount of theoretical work was carried out by Bruno Touschek already by June 1943. On the betatron, Touschek's contribution to the theoretical aspects of the project was highly valued and recognized by Widerøe, as described in details in a letter to Edoardo Amaldi and later in his autobiography.[85]

[82] In a letter to his parents, dated February 15th, 1943, Touschek mentions reading what appears to be Widerøe's article, which in fact was published at the beginning of that year.

[83] It is possible that Egerer was involved in this. In the 15th February 1943 letter, after mentioning reading "a stupid article" (Widerøe's?), Touschek mentions that Egerer makes crazy plans ("wüste Pläne"), like a possible assignment from the Wehrmacht to build [...] a cyclotron.

[84] In the June letter he also mentions his studies on group theory, on which he hoped to become an expert by the end of the war.

[85] "He was of great help to us in understanding and explaining the complications of electron kinetics. Especially the problems associated with the injection of the electrons from the outside to the stable orbit where they are being accelerated. Touschek showed that this process could be described by a Painlevé differential equation [...]". R. Widerøe to E. Amaldi, November 10, 1979, Amaldi Archive, Physics Department, Sapienza University of Rome, Box 524, Folder 4, Subfolder 2.

Similar considerations concerning Touschek's contributions to the design work for the betatron can be found in [71].[86]

After an initial period, during which he visited Germany a few times, Widerøe had progressed far enough with his betatron studies and, in late August, moved to Germany for the actual construction of the betatron. He started working in Hamburg in August 1943 in collaboration with the physicist Rudolf Kollath and then with Touschek, whom he invited to join for the theoretical work. In Hamburg Widerøe had his first contacts with Richard Seifert, who was the owner and director of a medium sized factory already manufacturing devices for X-rays since 1897, only two years after Röntgen's discovery. Widerøe and his group realized that the place best suited to build the betatron was at the C. H. F. Müller factory, which produced big X-ray-tubes and radio-valves, and had thus a great experience in glass-blowing and vacuum techniques, the basic tools of accelerator designs at the time. Incredibly, the so called Röntgenmüllers building had survived the bombings, so that it was possible to start constructing the betatron already in autumn 1943. Working in Hamburg was not easy during the war. Although Hamburg was regarded as a "relatively safe" place after the intensive bombing attacks of the early summer, being the major port of the North as well as an industrial center, Hamburg was also the site of the oldest dynamite factory and continued to be the target of several strategic allied bombing missions.[87] New air attacks often forced the betatron group to flee to the basement, and wait until danger had passed. There was always a big question as to whether the betatron-tube was still sealed and the vacuum still intact. Throughout this period, Touschek kept sending to his parents detailed accounts of his daily life and the devastating effects of bombing on German cities. At the end of a long letter written to his parents on November 27, 1943, completely dedicated to the description of his life in Berlin which was bombed night after night, he made a drawing of destroyed buildings, which we reproduce in Fig. 8.

On March 20, 1944, Touschek announced to his parents that Widerøe had required his presence in Hamburg "in order to accelerate the work." Thus, starting from April-May 1944, Bruno started moving between Berlin and Hamburg. During the summer of 1944, the betatron was put in operation by Widerøe and Kollath. The first test runs showed that the bremsstrahlung produced had an energy of 12-14 MeV. On July 8, 1944, Touschek wrote to his parents: "I like Hamburg, I am not studying so much [. . .]. I am always invited to very interesting conferences and seminars. However, this is all what I am doing for my future. Widerøe and I are planning to write a book on

[86] "In collaboration with the design work of Widerøe, a considerable amount of theoretical work was carried out by Touschek which was known to have been of invaluable aid in the development of the 15-Mv accelerator." The list of works carried out by Touschek in 1944–1945 is mentioned in a document preserved in Widerøe's archive at Eidgenössische Technische Hochschule Zürich (Handschriften und Autographen der ETH-Bibliothek, 175 Rolf Widerøe, "Akten, Korrespondenz und andere Dokumente zu Werk und Leben", available at http://e-collection.ethbib.ethz.ch/). This work was never published nor mentioned by Touschek in any Curriculum Vitae.

[87] Since the mid 1942, the United States Army Air Forces had arrived in the United Kingdom, and a combined offensive plan had been put in operation for bombing Germany. The combined strategic bombing offensive began on 4 March 1943. During the summer, the battle of Hamburg, codenamed Operation Gomorrah, took place. Commencing on the night of July 24, 1943, what was later considered the heaviest assault in the history of aerial warfare, continued until August 3. Hundreds tons of bombs were dropped which included incendiary bombs. During the course of five air attacks, which almost completely destroyed Hamburg's centre and some outer areas, over two-thirds of Hamburg's population fled the city, but 40,000–50,000 people were, and over a million of civilian were left homeless.

Fig. 8. Touschek's drawing of a bombed building from a letter to his father, November 27, 1943.

the Rheotron,[88] in the meantime he has collected a lot of material [...]". On July 20 he wrote again: "The war must be going to end soon [...]". On July 30, after a new bombing raid during the previous night, he reassured them: "For your peace of mind, I can say that nothing happened during the night between Friday and Saturday: all I wanted to do was to be able to sleep [...]. Earlier in the week I have presented my works on nuclear theory (Yukawa theory) to Prof. Lenz for him to check them. Lenz is keen that we meet every week to discuss and the first meeting is fixed to be next Saturday, with a very selected audience [...]. I worked all night [...]".

In these letter there is mention of repeated bomb alarms. On August 14 he was hoping to visit his parents in Vienna, and explicitely mentions his starting a vacation on August 28: "[...] if you agree, I shall come to Vienna, and it will be for 3 weeks. Send your next letter to Berlin, I will arrive on 24th." In a letter written on September 11 he mentions his return journey, and includes the drawing reproduced in Fig. 9.

From Widerøe's autobiography [9] we learn that by the autumn of 1944 a meeting took place at the Kaiser-Wilhelm Institute in Berlin, during which the activity with the betatron was presented. According to Widerøe, Heisenberg or Walter Gerlach must have organized it. It had become clear that the machine could be an interesting research tool both for nuclear physics and for medical applications. In the meantime, following Max Steenbeck's proposal, Konrad Gund built a 6 MeV betatron in the

88 Rheotron was one of the names used to indicate the betatron.

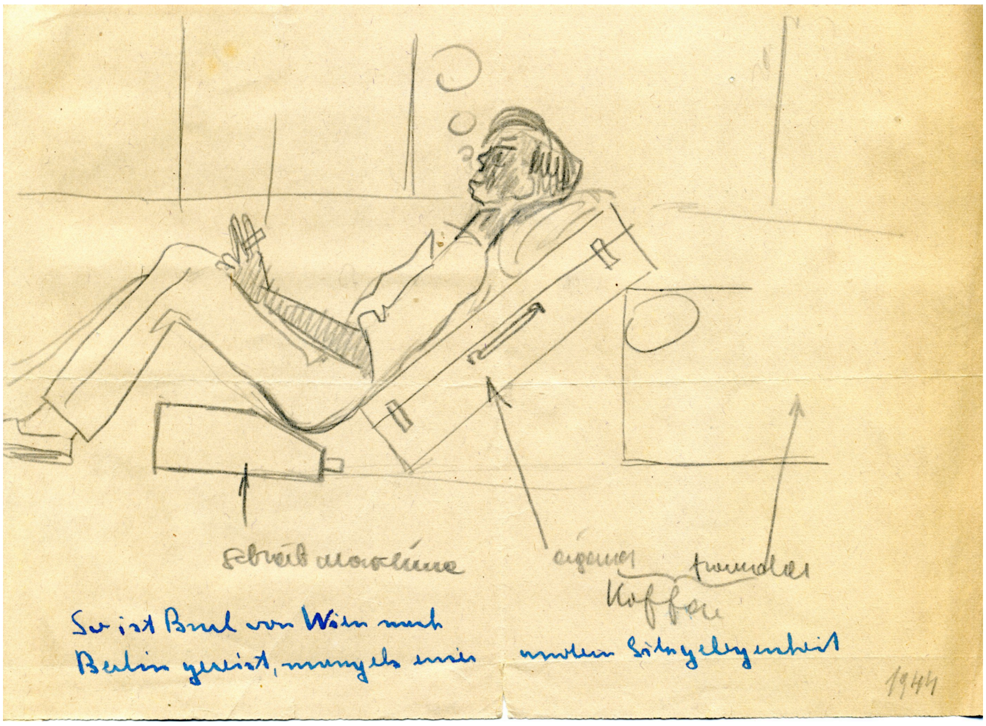


Fig. 9. Unpublished drawing by Bruno Touschek, extracted from a letter to his father, dated September 11, 1944. The caption reads: "Thus is Burl [family nickname for Bruno] travelling from Wien to Berlin for lack of seating-accomodation", and the arrows in English translation read as "typewriter" and "my own [and] somebody else's suitcase".

Siemens-Reiniger factory. Initially, this betatron had problems with the vacuum and did not work, as recalled by Widerøe; it was taken to Göttingen after the end of the war and later employed for medical uses.

Spanning the period from September 11, 1944 until March 13, 1945, Bruno's letters to his parents describe his life and work on the betatron and with Widerøe's group. The March 13 letter is the last to reach his family before the end of the war and describes Bruno's frenetic activity during the previous days and the anxious movements between Hamburg and Kellinghusen, where the betatron had been moved according to the orders. In fact, as the British Army was approaching Hamburg, the German Aviation Ministry had ordered the betatron to be moved away, to Kellinghusen, near Wrist, some 40 km north of Hamburg, and the group formed by Widerøe and his collaborators Rudolf Kollath, Gerhard Schuman and Touschek, had been busy with transportation of the last materials, away from Hamburg and to Kellinghusen. In the March 13th letter, we read that Touschek had been going back and forth during the whole day, so that his last words in the letter written from Kellinghusen, and probably terminated on the following day, were: "In the meantime Wednesday has arrived, and I am really exhausted." No more letters reached Touschek's family until the end of the war. Following this last letter, there are two telegrams sent from Kellinghusen to Touschek's father in Vienna, the first from Bruno himself, sending his new address in Kellinghusen, and a second, signed by an unidentified sender, Erhorn, who writes that the son is well, but cannot answer their queries. On October 22nd, 1945, a letter dated June 22, 1945 reached Vienna, followed in November by a second one, dated

November 17, 1945. These post-war letters constitute a very important document, both about Touschek's life, but also about conditions in Germany while the war was coming to a close. They provide a clear sequence of dates about Touschek's movement during that dramatic period. This period includes Touschek's imprisonment, the subsequent march towards the Kiel concentration camp, and the shooting episode, which we shall describe below, and which probably saved Touschek's life. They also establish clearly that Widerøe was in Germany until April 10 or 11, 1945, contrary to what is stated in [9], where Widerøe's return to Oslo is dated in March.[89] In the following we shall present the March–April events, following the description given in the letters by Touschek himself. In case of contradiction with Amaldi [7,8] or Widerøe [9], we rely on the letters.

According to the above mentioned letters, on Thursday, 15th of March, Touschek was still in Kellinghusen, and on Friday, 16th of March, left for Hamburg and arrived there by night, during an air raid. On the following morning he was arrested and taken to prison to Fuhlsbüttel, near Hamburg, under suspicion of espionage. To render clear Touschek's movements during these last days, we show in Fig. 10 we a map of the region.

Fig. 10. A map of the region around Hamburg (lower center): on the upper right is Kiel, where Touschek and the other prisoners were being brought to by the SS guards on 11 April 1945, in the left center Kellinghusen, where the betatron was brought from Hamburg in March 1945, and nearby the town of Itzehoe, mentioned in Touschek's letters to his parents.

While in prison, as described in Touschek's letter to his father, Widerøe would go to visit him, bring him books and continue discussing about the physics and their ideas. Widerøe also, in his autobiography, remembers bringing him food and cigarettes and a copy of the classic book by Heitler *The Quantum theory of Radiation* [72]. On this book, it is said that Touschek wrote, with invisible ink, a short note on "Radiation damping in betatrons" [7,8].[90]

From this narrative, there emerge the intellectual development and studies which would lead Bruno Touschek many years later to the first electron-positron storage ring and to a program of administering radiative corrections to high energy electron positron scattering. But all this was yet to come. In early 1945, while the Allied were progressing through Europe, Touschek met the most dramatic point

[89] Actually, in [70] it is told that Widerøe went back to Norway in April 1945.

[90] The question of writing with invisible ink is mysterious. No mention of such episode can be found in Touschek's letters. In Amaldi's original typescript, after February 28th, 1978, there is mention of a note written in "modo invisibile", "invisible way", with a question mark. A related note, authored by Touschek, dated 1945, and entitled "Zur Frage der Strahlendämpfung im Betatron" is listed in the catalogue of R. Widerøe's papers preserved at the Library of the Wissenschaftshistorische Sammlungen of Eidgenössische Technische Hochschule (ETH), in Zurich.

of his life. We have his direct account of a famous incident in a letter he wrote to his father shortly after the war ended. We have extracted some details, as follows.
"Kellinghusen, 1945, June 22nd
Dear parents, [...] I have not received any news from you for a very long time [...] [I shall now give you] a brief update about what happened to me [...]. After 3 weeks in prison in Hamburg, where I was because of suspected espionage, the prison was evacuated [and] all the (200) prisoners were put in a long line towards Kiel [concentration camp]. In front of us, behind, and on the sides, marched the SS guards. Near Hamburg [...]. I fell to the ground [...] and the guards pushed me in the gutter, near the road, and shot at me. One shot went through my left ear, the other through the padding of my coat. [After they left me for dead] I went to the hospital, and was again made a prisoner and sent to Hamburg from prison to prison. This lasted about four weeks." We present a translation of the complete letter in Sec. 5.

After being set free on April 30, and during several months — at least until the end of 1945, according to what he wrote to his parents — Touschek was practically a prisoner in Kellinghusen before the whole situation of the Widerøe betatron was clarified with the British authorities, who decided to take the machine to England, near London, as part of the booty of war [73].[91] At the beginning of 1946 Bruno Touschek went to University of Göttingen to obtain his diploma, and then, for his final education, to Glasgow, where he obtained his doctorate in 1949. As discussed in the next subsection, this experience established Touschek's subsequent and seminal work of all the subsequent years.

When, in the 1950s, in Frascati, near Rome, an electron synchrotron was commissioned and finally designed and built a few years later, Touschek, who had moved to Rome in 1953 with an INFN position, was then ready and prepared to join the work taking place in the newly built INFN National Laboratories in Frascati.

3.3 Diploma at Göttingen

By the end of September 1945, Touschek must have received a letter from Sommerfeld, to whom he answered telling him he was working on "betatron calculations", on "neutrino theory" and "on radiation damping."[92]

In 1946, he went to Göttingen to continue his studies and get his diploma. The university town of Göttingen, respected for its longstanding and high tradition in the natural sciences, had been chosen by the British authorities as the center for the reconstruction of West German science. Max Planck had arrived there as a refugee on June 4, 1945, while Werner Heisenberg settled there at the beginning of 1946, after returning to Germany from internment in Great Britain. He organized a new Institute for Physics and made it flourish with the help of Carl Friedrich von Weizsäcker, Karl Wirtz and Erich R. Bagge.

The Siemens 6-MeV betatron built by Gund had been brought to Göttingen, where Wolfgang Paul later extracted the electron beam in order to study the reaction $e + D \to e + p + n$. On June 26 1946, Touschek obtained his "Diplom-Physiker"

[91] Manuscripts signed by Touschek regarding the theory of betatrons, and marked with the name of Kellinghusen are kept at the Library of the Wissenschaftshistorische Sammlungen of Eidgenössische Technische Hochschule, among Rolf Widerøe's documents: B. Touschek, Zur Theorie des Strahlentransformators; On the Starting of Electrons in the Betatron; Die magnetische Linsenstrasse und ihre Anwendung auf den Strahlen-Transformator (1945); Zur Frage der Strahlungsdämpfung im Betatron (1945).

[92] B. Touschek to A. Sommerfeld from Kellinghusen, September 28, 1945. Deutsches Museum Archive, NL089,013. Sommerfeld was very worried about his son Ernst, from whom he had not received any news since some time and actually nobody knew where he was.

(Diploma in Physics) with a thesis on the theory of the betatron, made under the supervision of Richard Becker, director of the Institute of Theoretical Physics and Hans Kopfermann,[93] and was appointed research worker at the Max Planck Institute of Göttingen, where he began to work under the direction of Heisenberg, with whom he continued to keep in contact during the following years. Touschek had first seen Heisenberg giving a public lecture in Vienna in 1939, and later had met him in Berlin. In an unpublished and undated manuscript, he recalls his impressions of him and talks about some problems they discussed together during Touschek's Göttingen days.[94] From letters of the period we learn that during the summer he spent some time in Wimbledon, where he reported the British authorities on the betatron project. On November 24, 1946, he announced to his parents that an article on the double β-decay, was ready for publication [74].[95]

3.4 Glasgow

At the beginning of April 1947, Bruno Touschek settled in Glasgow with a scholarship of the Department of Scientific and Industrial Research. A the time, there was active work to design and construct a 300 MeV synchrotron. Bruno Touschek joined the work, which was taking place under Philip I. Dee, director of the Department of Natural Philosophy.

This period in Touschek's life, albeit relatively short, from the spring of 1948 to the end of 1952, is very important for his future work both in accelerators and in theoretical physics. His work with Dee and J. C. Gunn clearly built upon his earlier interest with Widerøe; during the Glasgow period Touschek studied in depth problems related to the working of the 30-MeV synchrotron, as well as to the construction of the 300 MeV machine.[96] Later, the work with Walter Thirring, who was also a young post-doc in Glasgow [75], was connected with his wider interest for electrodynamic

[93] See Touschek's Studienbuch and Diplom in Bruno Touschek's personal papers preserved by Elspeth Yonge Touschek.

[94] "First impressions: Common sense. The word I remember to have heard him use was "vernunftig"= reasonable. Then a phrase: "Das wollen wir einmal versuchsweise nicht glauben." [∼ To try it out, let's not believe it for now]. In Göttingen I attended his lectures on the quantum theory of fields. It was not a good lecture course, but there was one lecture, among them, which for me was a complete eye-opener: the harmonic oscillator and its quantization. I had learned Q. T. from Sommerfeld's "Wellenmechanisch Ergänzungsband" and I had tried Diracs famous book, both of which lean heavily on wave mechanics. His lecture opened my understanding to the mechanical approach [...]. The problem which bothered H. and which he asked me to unravel was "double β-decay". Haxel felt he could just do it (experimentally) and I ran into the difficulty of distinguishing what was arbitrary and what was sound in Fermi's theory of "weak interactions." I saw that clearly in 1947, but what I wrote then was riddled by stupid mistakes, which H. did not – or did not want to – see." B. Touschek, "Remarks on the influence of Heisenberg on physicists," undated manuscript, Bruno Touschek's personal papers preserved by Elspeth Yonge Touschek.

[95] Touschek to his parents, November 24, 1946. Actually the article was published much later, on January 1948. It appears that this research argument was suggested by Urban when Touschek left from Vienna, according to what the former wrote later to Amaldi on June 3, 1980, Amaldi Archive, Physics Department, Sapienza University of Rome, Box 524, Folder 4, Subfolder 4.

[96] Correspondence and documents of the period clearly show his involvement both in the building of the new synchrotron, and in his contribution to clarify problems with a betatron machine in Manchester. Bruno Touschek Archive, Physics Department, Sapienza University of Rome, Box 3, Folders 1, 4, 5, 6 and 7 and Box 1, Folder 1.

processes and with relativistic quantum electrodynamics, whose study constituted, at the time, the new physics frontier. In Fig. 11 we show a cutting from a local newspaper with a photograph of Touschek with Philip Dee and other colleagues in front of the model of the 300 MeV Synchrotron.

The Home Of The Synchrotron

Prof. Philip Dee (extreme right) pointing out to fellow research workers features on a model of the new synchrotron block to be built at Glasgow University. Others are (left to right) Mr. A. C. Robb, Dr. S. C. Curran and Mr. B. Touschek.

NO DANGER TO CITY FROM A-PLANT

"THERE will not be the slightest danger to anybody in the neighbourhood of this machine. I want to make that clear because I know there are a lot of stories going around."

Thus Professor Philip Dee, leader of the research team which will probe atom secrets at Glasgow University, yesterday scotched alarmist rumours which have sprung up following the announcement that a giant 300-million volt synchrotron producing 30 million volt X-rays is to be installed there.

The tall, dark, sparely-built Professor added: "Long before anybody outside would be affected in the slightest degree, those inside would be dying like rats. So people outside are certainly very safe—we are not going to kill ourselves, and we are going to be up against the thing."

The Professor was showing reporters a model of the new building which will house Britain's biggest synchrotron.

The machine will be sunk in a basement 20ft. below ground level, with 5ft. concrete slabs separating it from a main hall and research rooms above.

More important to the physicists than the synchrotron itself will be the beam produced, which will travel through a tube to a beam room into which targets will be shot through slits to test matter's reaction to 30-million volt X-rays.

BENEFITS

What are likely to be the benefits to society and medical science? His answer:

"It would be a very bold person who said what would be the consequences of understanding the structure of the nucleus.

"We physicists are not indifferent to what comes out of it. But it is best that things should be allowed to grow out of it naturally, rather than that we direct our efforts to a specific end."

Fig. 11. B. Touschek in Glasgow and a comment from a local newspaper.

Touschek submitted his first paper for publication on October 11 of 1947; it dealt with excitation of nuclei by electrons [76], a research which he continued to carry on during the following year and which became the basis for his Ph.D. dissertation. During the months December 1947 and January 1948, Touschek carried out researches on different issues. While absorption-measurements with the already existing 30 MeV electron synchrotron were being prepared, a ionization chamber had been ordered and a magnetic collimator was being designed, Touschek made accurate calculations for using carbon as an absorber. He also worked out a solution for the problem regarding statistics of 'effective' track-lengths in an ionization chamber with radius comparable but larger than range of particles emitted from sources randomly distributed over the gas of the chamber.[97] In the meantime, Touschek held "triangular discussion"

[97] At that time, Dee was particularly interested in studying the disintegration of atomic nuclei with the Wilson cloud chamber technique, for which in 1952 he won the Hughes Medal.

between Heisenberg and N. Hu in Copenhagen on questions regarding the analytic behavior of the S-matrix.[98]

Touschek's research report for the period February 1 to April 30, 1948, mentions submission of the review paper on the synchrotron [77] and work connected with "Heisenberg's theory of the η-matrix" : "In March – after a conversation with Prof. Heisenberg in Manchester I started closer investigation on a model system (meson-field in interaction with an oscillator) which seemed rather promising. Heisenberg wrote on April 20th: 'the example you described in your last letter seems to me to be an extraordinarily reasonable choice [...]. At present it appears, as if the model in question did not contain particle-production at all." As a sideline research Touschek worked on production of mesons in fission processes and determination of matrix-elemens for neutron-nuclear interaction.[99] During the period 1947–1948 Bruno Touschek published several papers on this issue, alone or in collaboration with other people [78–82]. On November 5, 1949, he was awarded his Ph.D. with a thesis entitled "Collisions between electrons and nuclei" which represented a review of the work on electron excitation and production of mesons by electrons carried out by Touschek in collaboration with I. N. Sneddon during the years 1947 to 1949.[100] During the year 1949 Touschek published a series of works on arguments reviewed in his thesis [83, 84]. In Fig. 12, we show Touschek in Glasgow together with Samuel C. Curran[101].

After his Ph.D. he became Nuffield lecturer and from the autumn 1950 he worked on the covariant formulation of the Bloch-Nordsieck method with his friend Walter Thirring who had arrived in Glasgow as Nuffield Fellow [85]. During his Glasgow years Touschek was in contact with Max Born, who had become Tait Professor in Edinburgh after leaving Germany in 1933. Touschek often visited him in Edinburgh and helped him to edit the new edition of his *Atomic Physics*, a series of lectures that Born had given in Germany in 1933, later published in Glasgow in 1935. Born thanked him in the preface "for scrutinizing and criticizing the whole script and for many valuable suggestions, in particular about β-decay and meson theory [86].[102] In 1950 and 1951 he published works on the production of π-mesons, and a paper on "A perturbation treatment of closed states in quantized field theories" [87–89].

From letters to his parents, and from a letter written to Arnold Sommerfeld on October 5, 1950, we learn that he was unhappy in Glasgow, and that he hoped to find a different position.[103] On June 20, 1951, he writes to his parents that he is planning to buy a motorbyke to travel through Europe and visit Rome during the summer.

[98] "Research carried out during the months December 1947 & January 1948", Bruno Touschek Archive, Physics Department, Sapienza University of Rome, Box 3, Folder 1; W. Heisenberg to B. Touschek from Cambridge: January 28, February 23, 1948; from Göttingen: April 20, 1948. Bruno Touschek Archive, Box 1, Folder 1.

[99] "Research report for February 1s to April 30th 1948", Bruno Touschek Archive, Physics Department, Sapienza University of Rome, Box 3, Folder 1.

[100] One of us (L.B.) is indebted to prof. D. H. Saxon, of Glasgow University, for sending a copy of Touschek's thesis.

[101] Sir Samuel Curran (1912-1998) was Lecturer in the Physics Department of University of Glasgow from 1945 until 1955. In 1959 he was appointed Principal of the Royal College of Science and Technology and was instrumental in leading the institution to Universiy status at the beginning of the 1950s (Courtesy of University of Glasgow).

[102] Touschek recalled that during this work he discovered the universality of beta interaction and prepared an appendix where he discussed analogies between nuclear β-decay and the decay of μ and charged π-mesons, but he later realized that in the meantime Giampiero Puppi had already done something similar. Bruno Touschek"Curriculum Vitae", Bruno Touschek's personal papers preserved by Elspeth Yonge Touschek.

[103] B. Touschek to Arnold Sommerfeld, October 5, 1950, Deutsches Museum Archive, NL 089,013.

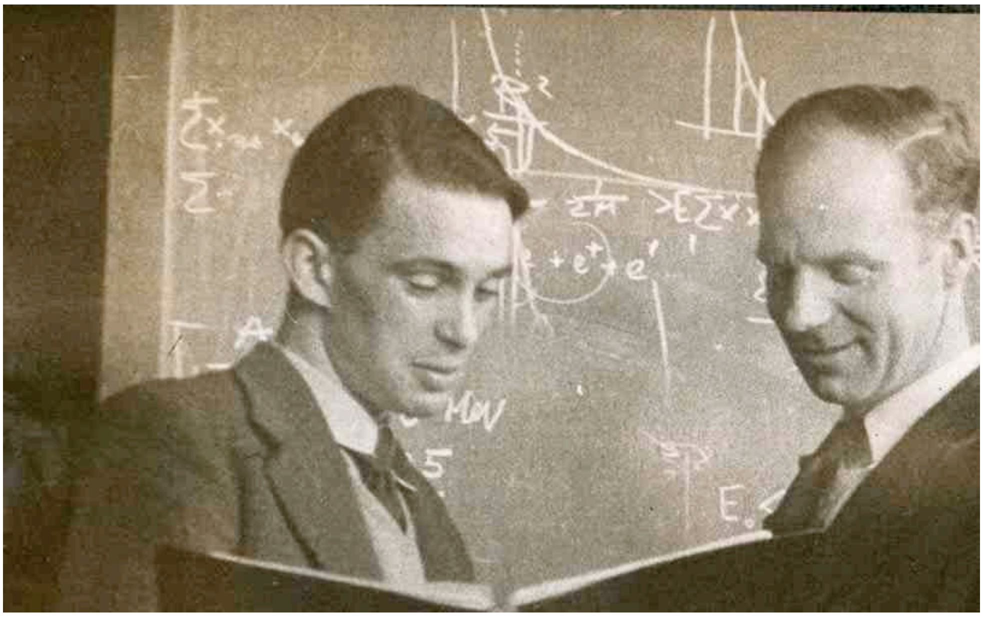


Fig. 12. Touschek in Glasgow with Samuel C. Curran (identification courtesy of Glasgow University).

On November 9 he is announcing that he has tried to obtain a position in Rome, and that Bruno Ferretti (professor of theoretical physics at Sapienza University of Rome) has written him, but the matter was still to be perfected. Only in December of the following year Touschek will succeed in moving to Italy. On December 30, 1952, he is writing to his parents from Rome with enthusiasm: "In the Institute I will occupy Blackett's room after his leaving [...]. Roman food and wine make me feel well and also the climate – even now in winter – has nothing to share with Glasgow. The Institute is really excellent. At the moment there are two Nobel Prize (Pauli and Blackett) and a possible candidate and other people are very interesting, too."

4 Touschek's impact on theoretical developments in Rome and Frascati

We have described, in Sect. 2, the events which followed Touschek's arrival in Rome and the construction of AdA. In this section, we shall present his later work and illustrate the influence he exerted on theoretical physics at the University of Rome and Frascati.

Soon after AdA had started working, Touschek already thought of a bigger machine, one which could do real physics, with a higher energy, ADONE, namely a bigger, better, more beautiful AdA. The proposal is signed by Touschek, Carlo Bernardini and Giorgio Ghigo (AdA proposers), together with Fernando Amman and Raoul Gatto. Amman became the director of the ADONE project and had it ready for commissioning in 1968.

Gatto[104] was at the time a young Assistant Professor in Rome, interested in all which was happening in Frascati. After Panofsky's seminar and Touschek's excitement

[104] R. Gatto is presently Emeritus Professor at University of Geneva, Switzerland. After a few years at U. of Rome, he moved to Florence, as Professor of Theoretical Physics and

on the possibility of electron-positron collisions, Gatto, together with Nicola Cabibbo, had started exploring the physics which could be probed by such collisions [48,49]. In the appearing of Gatto and Touschek's names together in the ADONE proposal, we see the close collaboration of theory, technology and experimentation which was present in Rome and Frascati at the time. It also highlights another contribution of Bruno Touschek, namely his influence on the development and successes of the Rome University theoretical physics school. As already mentioned, Touschek had many students, his first two having been Nicola Cabibbo and Francesco Calogero, to be followed by Paolo Di Vecchia, Sergio Ferrara, Giovanni Gallavotti, Giancarlo Rossi, and many others.[105] Through the 10 years spanning the proposal to build AdA and the construction of ADONE from the late '50s until the late '60s, Bruno Touschek was a referral for most of the physics students enrolling in unprecedented number at the University of Rome, following the wave of interest generated by the launch of Sputnik.[106] He was, in those years, a charismatic personality, a great teacher, of brilliance and clarity, a scientist who had known the famous physicists of the German school and a driving figure.
Because of AdA and ADONE, many teoretical physics theses came to be, some with Bruno Touschek, others with Cabibbo or with Gatto. At first, single and double bremsstrahlung processes were studied, but soon Touschek became concerned with the high energy limit of soft photon emission, a problem he had been interested when in Glasgow. It became clear to Touschek that, at ADONE's center of mass energy of $\sqrt{s} \leq 3.0\ GeV$, summation of an infinite number of soft photons would be a necessity for any precision measurement. Using experience in QED processes accumulated both during the war and in Glasgow in his work with Walter Thirring, Touschek prepared a work on summation of soft photons in high energy reactions, which had a strong impact on subsequent theoretical work in Frascati and in University of Rome [90]. Touschek's concern was indeed well founded: as the center of mass energies reached by electron-positron colliders increased, resummation techniques[107] would soon become an indispensable tool to extract theoret-

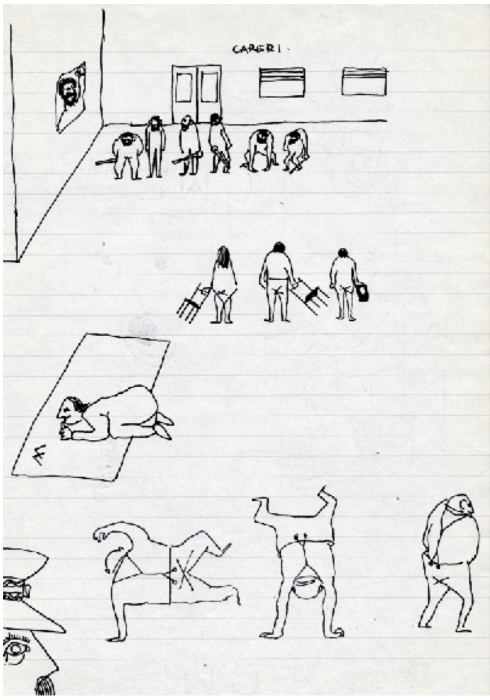


Fig. 13. Undated drawings by Bruno Touschek describing the 1968 student unrest in University of Rome.

trained many students, also known as "gattini" [kittens]. Some of the "gattini", such as Guido Altarelli, Franco Buccella, Luciano Maiani, Giuliano Preparata, Gabriele Veneziano, to name just a few, were later to give important contributions to theoretical particle physics. Gatto was also Chief Editor of Physics Letters B for many years.

[105] A list, of Touschek' students can be found in [7].

[106] As mentioned, the 1959 broadcast in national television of physics lectures by the Director of the Frascati Laboratories, Giorgio Salvini, also contributed to such interest.

[107] The term *resummation* was not used during Touschek's times and came in use later, in connection with Quantum Chromodynamics.

ical quantities from the data, as it proved to be the case when the J/Ψ was discovered [91]. Unfortunately, the 1968 student unrest in Rome and other political problems in Frascati delayed ADONE's operation for a whole year [11,18]. In Fig. 13 we show one of the many drawings which Touschek dedicated to the 1968 unrest in Rome University.

The need for a special formalism to apply radiative corrections to very narrow resonance production in electron-positron annihilation had seemed a rather virtual one in 1968, when he had suggested the problem to the young theorists of his group in Frascati, but it became a reality a few years later with the discovery of the J/Ψ. Another problem that Touschek was very keen in solving, but could not really complete, was the angular distribution of resummed photon momenta. He did not live to see how important the problem became in Quantum Chromodynamics. In the following we shall discuss in more details some of these issues. At the end of this section, we shall also mention the influence of Touschek's teaching and experience in the development of statistical mechanics studies at University of Rome.

4.1 The "Infra-red catastrophe"

In 1948 Bruno Touschek was in Glasgow and became interested in the infrared catastrophe phenomenon, namely the fact that in any process in which charged particles scatter from an initial into a final state, i.e. are created or destroyed, the probability of emission of light quanta diverges as the photon frequency goes to zero. The problem had been pointed out by Bloch and Nordsieck in a paper in 1937. In [92] Bloch and Nordsieck observed that previous methods of treating radiative corrections to scattering processes were defective in that they predicted infinitely large low frequency corrections to the transition probabilities. This was evident from the $d\omega/\omega$ spectrum for single photon emission in electron scattering in a Coulomb field as described by Mott and Sommerfeld [93,94] and by Bethe and Heitler [95]. Bloch and Nordsieck had noticed that, while the ultraviolet difficulties are already inherent in the classical theory, the infrared divergence has no classical counterpart, and anticipated that only the probability for the simultaneous emission of infinitely many quanta can be finite and that the probability for emission of any finite number of them must vanish. They noticed that for emitted photons of frequency larger than a given ω_0 the probability of emitting each additional photon is proportional to $(e^2/\hbar c)\log[E/(\hbar\omega_0)]$, which becomes large as $\omega_0 \to 0$. Thus, the actual expansion is not $(e^2/\hbar c)$, which would be small, but a larger number, driven by the logarithm. This led them to analyze the scattering process in terms of what came to be called Bloch-Nordsieck states, namely states with one electron plus the electromagnetic field, and to substitute the expansion in $(e^2/\hbar c)$ with a more adequate one.

The important result of [92] was that, albeit the probability of emission of any finite number of quanta is zero in the $\omega \to 0$ limit, when summing on all possible numbers of emitted quanta, the total transition probability and the total radiatated energy were finite. This led Bloch and Nordsieck to anticipated that the mean total number of quanta had to be infinite. Thus the idea that any scattering process is always accompanied by an infinite number of soft photons was introduced and proved to be true in a non-covariant formalism.

In [92] one sees the emergence of the concept of finite total energy, with exponentiation of the single photon spectrum which is logarithmically divergent such that the probability for a finite number of emitted photons is always zero. On the other hand, when summation is done over all possible photon numbers and configurations, the result is finite. Clearly there was still something missing because there is no hint of how to really cure the infrared divergence. In addition the language used is still non-covariant.

Before going to the covariant formulation, we notice that the crucial argument relies on the transition probability being proportional to

$$\Pi_{s\lambda} e^{-\bar{n}_{s\lambda}} \frac{\bar{n}_{s\lambda}^{n_{s\lambda}}}{n_{s\lambda}!} \tag{4}$$

namely to a product of Poisson distributions, each of them describing the independent emission of $n_{s\lambda}$ soft photons.

The Bloch and Nordsieck formulation and the subsequently proposed solution were framed in a non covariant language. When Touschek and Thirring met in Glasgow, after the war and with second quantization and relativistic quantum field theory, they saw the need to reformulate the problem in a covariant formalism. As Touschek and Thirring say in the introduction of their paper [85], the results they obtain were not new and had been discussed by several authors, but the importance of the Bloch Nordsieck problem, as the only one which admits an accurate solution, justified a general reformulation. It should be stressed that the simplification which enabled one to find an accurate solution rested on the neglect of the recoil of the source particles [92]. Using this approximation Touschek and Thirring calculated the average number of photons emitted in a momentum interval Δ. In their paper Touschek and Thirring first derive their results for a source scalar field, then they generalize it to a vector source function $j_\mu(x)$ of a point-like electron, i.e.

$$j_\mu(x) = e \int p_\mu(\tau)\delta(x - \tau p(\tau))d\tau \tag{5}$$

where $p_\mu(\tau) = p_\mu$ for the (proper) time τ less than 0 and $p_\mu(\tau) = p'_\mu$ for τ larger than 0. Notice that the sudden change in momentum imposes the restriction that in order to apply the results to a real scattering process, the photon frequencies should always be much smaller than $1/\tau$, where τ is the effective time of collision. Otherwise the approximation (of a sudden change in momentum) will break down. One then obtains

$$j_\mu(k) = e\big(\frac{p_\mu}{(pk)} - \frac{p'_\mu}{(p'k)}\big) \tag{6}$$

and the average number of quanta $\bar{n}$ now becomes

$$\bar{n} = \frac{e^2}{(2\pi)^3}\int_\Delta d^4k\delta(k^2-\mu^2)\big[\frac{(p\epsilon)}{(pk)} - \frac{(p'\epsilon)}{(p'k)}\big]^2 \tag{7}$$

where ϵ is a polarization vector.

4.2 Schwinger's Ansatz on the exponentiation of the infrared factor and status of the field in early '60s

The solution found by Bloch and Nordsiek and later brought into covariant form by Touschek and Thirring did not really solve the problem of electron scattering in an external field and of how to deal with finite energy losses. This problem was discussed and solved in the context of Quantum Electrodynamics, where the logarithmic divergence attributable to the infrared-catastrophe from emission of real light quanta of zero energy was compensated through the emission and absorption of virtual quanta. This cancellation was taking place in the cross-section, and not between amplitudes. In a short paper in 1949 and, shortly after, in the third of his classic QED papers, Julian Schwinger [96,97] examined the radiative corrections to (essentially elastic) scattering of an electron by a Coulomb field, computing second order corrections to the first order amplitude and then cancelling the divergence in the cross-section between these terms and the cross-section for real photon emission. The result, expressed as a fractional decrease δ in the differential cross-section for scattering through an angle θ in presence of an energy resolution ΔE of the scattered electron, is of order α and given by

$$\delta = \frac{2\alpha}{\pi} log(\frac{E}{\Delta E}) \times F(E, m, \theta) \tag{8}$$

where $F(E, m, \theta)$ in the extreme relativistic limit is just $\log(2E/m)$. Schwinger notices that δ diverges logarithmically in the limit $\Delta E \to 0$ and points out that this difficulty stems from the neglect of processes with more than one low frequency quantum. Well aware of the Bloch and Nordsieck result, he notices that it never happens that a scattering event is unaccompanied by the emission of quanta and proposes to replace the radiative correction factor $1-\delta$ with $e^{-\delta}$, with further terms in the series expansion of $e^{-\delta}$ expressing the effects of higher order processes involving multiple emission of soft photons.

In 1949 however, given the energies available for scattering experiments, the exponentiation of the radiative correction factor, was still far from being needed. As Schwinger points out, the actual correction to then available experiments, could be estimated to be at most about 10%. Almost twenty years had to pass before the exponentiation became an urgent matter, and $\alpha log(E/m)$, the factor which Touschek christianed the *Bond factor*, started to become so large that the first order correction, the double logarithm $\alpha log(E/\Delta E) log(2E/m)$ would climb to $20 \div 30\%$ and beyond.

In the 1950s, with Feynman diagrams technique available to the theoretical physics community, many higher order QED calculations came to be part of standard theoretical physics handbooks.

Many important contributions to the radiative correction problem appeared in the '50s and early '60s [98–103], with a major step in the calculation of infrared radiative corrections done in 1961 by Yennie, Frautschi and Suura (YFS) [104]. In their classic paper, they went though the cancellation of the infrared divergence at each order in perturbation theory in the cross-section and obtained the final compact expression for the probability of energy-momentum loss in a high energy reaction between charged particles. In their paper they compute higher and higher order photon emission in leading order in the light photon momentum, showing that the leading terms always come from emission from external legs in a scattering diagram. In parallel, order by order, they extract the infrared divergent term from the virtual diagrams, making the terms finite through the use of a minimum photon energy. They show that the result is just as valid using a minimum photon mass, and finally eliminate the minimum energy, showing the result to be finite in the infrared.

4.3 The *Bond factor* and the radiative corrections to e^+e^- experiments

After the construction of AdA, and the beginning of the construction of ADONE, as Ugo Amaldi remembers in [14], Bruno became seriously concerned with the success of ADONE experiments. The major problem to solve concerned the infrared radiative corrections to the proposed experiments. This was at the time an ongoing preoccupation. In the United States, Tsai [105] had been performing realistic radiative correction calculations to colliding beam experiments, which however were restricted to first order in α. Touschek realized that, at a machine like ADONE, the radiation factor, $\beta \propto \alpha \log(2E/m_e)$ would not be small and that it would be necessary to use the exponentiation advantage while also doing a calculation for a realistic apparatus. The problem was then to combine the realistic approach by Tsai and the theoretical

Fig. 14. Bruno Touschek, during the construction of ADONE, in Frascati around 1965, with colleagues. At Touschek's left is Italo Federico Quercia, Director of Frascati Laboratories.

formulation of the exponentiated infrared factors of [104]. In Fig. 14 we show Bruno Touschek in Frascati during the period of the construction of ADONE.

In the Spring of 1966, the Frascati theory group included Giovanni De Franceschi, Paolo Di Vecchia, Francesco Drago, Etim Etim, Giancarlo Rossi, Mario Greco and G.P., one of the authors of this paper. At the time, there was great interest in strong interaction physics, with Finite Energy Sum Rules and Current Algebra results. But Touschek knew that the success of experimentation on ADONE relied on precise radiative correction calculations. His approach was: "We must do the administration of the radiative corrections to electron positron experiments", in his words, "we must earn our bread and butter." He already had part of the work in his mind. The paper [90] starts with some fundamental considerations, which reflect the Bloch and Nordsieck approach to the problem, namely that the picture of an experimentalist as counting single photons as they emerge from a high energy scattering among charged particles is unrealistic. Then Touschek, to use his own words, charges perturbation theory with being unable to deal with the flood of soft photons which accompany any such reactions. Originally Bloch and Nordsiek had shown that, by neglecting the recoil of the emitting electron, the distribution of any finite number of quanta would follow a Poisson-type distribution, namely

$$P(\{n, \bar{n}\}) = \frac{1}{n!}\bar{n}^n e^{-\bar{n}} \tag{9}$$

and Touschek and Thirring had recast $\bar{n}$ in the covariant form. In [90], Touschek uses this distribution and adds to it the constraint of energy momentum conservation.

This is the major improvement, which has sometimes been neglected in subsequent applications of the method to strong interaction processes.

We shall now repeat the argument through which Touschek obtained the final 4-momentum probability distribution to have an energy momentum loss K_μ. The final expression is the same as the one proposed earlier by Yennie, Frautschi and Suura, but the derivation is very different and, because of its semi-classical derivation, its physical content more transparent. The paper also has a discussion on the energy scales which will become very important later, when dealing with resonant states, and in particular with J/Ψ production.

In [90] the probability of having a total energy-momentum loss K_μ in a charged particle scattering process, is obtained by considering all the possible ways in which $n_{\mathbf{k}}$ photons of momentum $\mathbf{k}$ can give rise to a given total energy loss K_μ and then summing on all the values of $\mathbf{k}$. In this formulation one obtains a total energy-momentum loss K_μ through emission of $n_{\mathbf{k}_1}$ photons of momentum $\mathbf{k}_1$, $n_{\mathbf{k}_2}$ photons of momentum $\mathbf{k}_2$ and so on. Since the photons are all emitted independently (the effect of their emission on the source particle is neglected), each one of these distributions is a Poisson distribution, and the probabilty of a 4-momentum loss in the interval d^4K is written as

$$d^4P(K) = \sum_{n_{\mathbf{k}}} \Pi_{\mathbf{k}} P(\{n_{\mathbf{k}}, \bar{n}_{\mathbf{k}}\})\delta^4(K - \sum_k k n_{\mathbf{k}}) d^4K \tag{10}$$

where the Bloch and Nordsiek's result of independent emission is introduced through the Poisson distribution and four momentum conservation is ensured through the 4-dimensional δ-function, which selects the distributions $\{n_{\mathbf{k}}, \bar{n}_{\mathbf{k}}\}$ with the right energy momentum loss K_μ. The final expression, obtained with methods of statistical mechanics was

$$d^4P(K) = \frac{d^4K}{(2\pi)^4} \int d^4x \; exp[-h(x) + iK \cdot x] \tag{11}$$

with

$$h(x) = \int d^3\bar{n}_{\mathbf{k}} \big(1 - exp[-ik \cdot x]\big) \tag{12}$$

This result is the same as in [99,104], but it was obtained in a simple, almost intuitive manner, and it appeared extraordinarily simple to the Frascati experimentalists, who were waiting for a precise calculation to apply to the ADONE data. Eq. (10) allows to obtain immediately the correction factor for the energy. By performing an integration over the 3-momentum $\mathbf{K}$, the distribution describing a total energy loss ω becomes

$$dP(\omega) = \frac{d\omega}{2\pi} \int_{\infty}^{\infty} dt \; exp[i\omega t - h(t)] = \mathcal{N}\beta \frac{d\omega}{\omega} \big(\frac{\omega}{E}\big)^\beta \tag{13}$$

where the already known result at the r.h.s. was obtained with a simple and elegant argument based on the fact that $dP(\omega) = 0$ for $\omega \leq 0$. $\mathcal{N}$ is a normalization factor [101–103], and, in the high energy limit,

$$\beta = \frac{4\alpha}{\pi} \big(\log \frac{2E}{m_e} - \frac{1}{2}\big) \tag{14}$$

Touschek named β the *Bond factor*, because its numerical value in the range of ADONE energies was around 0.07, the number made famous by the James Bond movies of the 1960s. This was just a small joke, but it held everybody's imagination for quite some time and is a typical example of Touschek's capacity for humour and making light of serious issues.

Although the radiative correction paper of 1967 was the last that Touschek wrote on this subject, his influence on the field continued in many ways and for longer than

Fig. 15. At left: AdA now, in Frascati, as preserved under a plexigass container. On the right: view of the ADONE building, now housing the accelerator DAFNE.

he himself may have imagined and came to know. While working on the above paper, he had suggested to his young collaborators two more relevant papers, one on the coherent state method [106], which indicates how to deal with soft photon emission in the amplitude rather than the cross-section, and one on infrared corrections to resonant process [107], which appeared (independently) shortly after a similar work by V.N. Baier, the theoretical physicist from Novosibirsk [108]. Although he did not sign these papers, Touschek had the original idea, gave suggestions during the preparation of the work and commented on the final versions. Both papers became relevant to study production of of narrow resonances at colliders. In later years, in addition to the work for the J/Ψ [91], the method he has inspired was used at LEP for the extraction of the parameters of the Z_0 [109]. The influence of Touschek is also reflected in one of the earlier and most famous works on resummation in QCD [110], whose authors were among the generation of theoretical physicists graduating with Gatto and Cabibbo.

Touschek's legacy in Frascati and in Italy is still very much alive today. In 1993 ADONE was definitely shut dow and construction for a new high luminosity e^+e^- accelerator for precision physics at 1 GeV c.m. energy was started. The project was approved by the Istituto Nazionale di Fisica Nucleare (INFN) under the presidency of Nicola Cabibbo and the machine was named DAFNE, Double Accelerator For Nice Experiments. DAFNE is housed in the ADONE building in Frascati, shown in Fig. 15. At left, in the same figure, one can see AdA, in the glass container which preserves it on the INFN Frascati National Laboratory grounds. DAFNE started producing physics in 1999 and plans for an upgrade both in energy and luminosity have been presented [111]. In the long range, INFN plans for an electron-positron machine at high luminosity operating at the CM energy of the Υ-resonance, a so called Super-B factory, are being considered.

4.4 The collective momentum distribution

Touschek's theoretical legacy is present also in a large body of work, still very active today, namely the transverse momentum distribution of soft radiation. Many days were spent in 1967 by Touschek and his young collaborators in trying to obtain a closed form for the momentum distribution

$$\frac{d^3P(K)}{d^3\mathbf{K}} = \int dK_0 \, \frac{d^4P(K)}{d^4K} = \int \frac{d^3\mathbf{x}}{(2\pi)^3} exp[-h(x) - i\mathbf{K}\cdot\mathbf{x}] \tag{15}$$

Short of a closed expression, which cannot be obtained, he showed [90] that the energy and the 3-momentum distributions factorize, i.e.

$$d^4P(K) = \beta\mathcal{N}^{-1}\frac{d\omega}{\omega}(\frac{\omega}{E})^\beta A(\mathbf{u})d^3\mathbf{u} \tag{16}$$

with $\mathbf{u} = \mathbf{K}/\omega$ and the momentum function $A(\mathbf{u})$ well approximated by a first order expansion in the fine structure constant α. Since in the QED case the angular distribution of the collective radiation was estimated as being well reproduced by the first order contribution,[108] the problem was left dormant.

However, in 1976, focusing on the transverse momentum rather that the 3-momentum distribution, the problem was revived and the reference to Touschek's work on radiative corrections and the memory of the time spent by him on the problem came again to life. In [112], the transverse momentum distribution for soft radiation was obtained from the Bloch-Nordsieck method integrating Eq.(10) in both energy and longitudinal momentum as

$$d^2\ P(K_\perp) = d^2\mathbf{K}_\perp \int d^2\mathbf{x}_\perp(2\pi)^2 exp[-h(\mathbf{x}_\perp) - i\mathbf{K}_\perp \cdot \mathbf{x}_\perp] \tag{17}$$

Working within an abelian theory, but with a large coupling costant, approximations were proposed for the function $h(\mathbf{x}_\perp)$ such as to allow a closed form for Eq.(17). An exponentially decreasing p_t-distributions for hadronic particles in high energy hadronic collisions in agreement with experiments [113] was then obtained.

At the same time and all along, resummation had also been developed by the great Russian theoretical physics school, starting with Sudakov's paper [100] in QED. In 1978, from the Russian school there came a seminal work on the transverse momentum distribution of QCD radiation [114,115], in which soft gluons were resummed with a running coupling constant. This was followed very soon by a similar pivotal work from Frascati and University of Rome [116]. In subsequent years, there appeared stlll other works on resummation traceable to Touschek's influence, including the application of soft gluon resummation techniques to calculate the transverse momentum distribution of $\mu^+\mu^-$ pairs (Drell-Yan pairs) [117] and the W-boson transverse momentum [118]. But then Touschek was no longer alive. As a conclusion to this description, we stress that the problem of soft gluon resummation is still very much alive today. The question of how to access the infrared limit, where perturbative QCD fails and the large distance behaviour of the theory plays a major role, is still unsolved.

4.5 The book *Meccanica statistica*

As mentioned, the resummed expression for soft photon emission given in Eq.(10) was obtained using the methods of statistical mechanics, which Touschek had studied in Göttingen and in Glasgow. His deep understanding of this subject is reflected in the book *Meccanica statistica* [119], which he wrote together with his student and collaborator Giancarlo Rossi.[109]

The first version of the book dates back to the winter of 1967. It was the result of a long process which started two years before with the publication of the notes that

[108] The usefulness of such expressions for experimentalists working on electron-positron collisions was recently remembered by Francois Richard, in a talk given at the *Bruno Touschek Memorial Lectures*, Frascati, November 30th, 2010.

[109] Parts of this section have been contributed by G. Rossi, who graduated with Touschek in 1967 and is now Professor of Theoretical Physics at University of Tor Vergata, Rome.

Giancarlo Rossi took when, as a fourth year Physics student, was following the course of Statistical Mechanics held by Touschek at La Sapienza in 1965. The notes, revised by Touschek himself, were published by a local Editor, La Goliardica, as lecture-notes for students. At the same time, having in mind the idea of finally publishing a book on Statistical Mechanics, Touschek started to write in English with the help of the beloved Olivetti Lettera 22 his version of the lectures he was delivering.

The final manuscript was published in Italian by Boringhieri in 1970 in the Series "Programma di Matematica Fisica Elettronica" with the title *Meccanica Statistica*. It finally resulted from the intersection of the English version written by Touschek with the one Rossi had elaborated in Italian.

In the long process of deciding the content of the book and the style of the text, Touschek's guiding idea and main concern were always clarity, as the book was supposed to be addressed to undergraduate students. For this reason the chosen language was plain and simple and it was decided to have at the end of each chapter a summary of the results and main ideas that were successively developed. Simplicity did not mean that all the subtleties inherent in the construction of Statistical Mechanics should be overlooked. Quite the contrary! Not only in the book standard subjects, like the construction of the various statistical ensembles, the proof of their equivalence or the derivation of the Master Equation, have been inserted and discussed in a somewhat original though elementary way, but unsolved conceptual problems were also addressed. Among others it is worth mentioning two of them since they drew the attention of the physics community at large as witnessed by the significant interest they spurred in the specialized literature. The first topic is a simple proposal to understand the apparent antinomy between microscopic reversibility and macroscopic irreversibility. The second is the solution of the problem posed by definition of temperature for a moving body in Special Relativity.

It is important to conclude these considerations on the birth and the content of the book *Meccanica Statistica* by observing that, despite the fact that Touschek had been lecturing on the subject for only 4 or 5 years at Sapienza University of Rome (at a certain point he moved to the course of Metodi Matematici della Fisica), his cultural legacy had a large impact on the development of theoretical physics in Rome. The roots of the many important contributions that Italian physicists have given to a number of research fields related to Statistical Mechanics (among which the theory of Spin Glasses and Complex Systems [120,121], Lattice QCD [122] and the emerging field of Biophysics) can be traced back to the crucial influence exerted by Touschek on a whole generation of physicists in the 60s and early 70s.

5 Unpublished correspondence: Letters to his parents

We present here an English translation of the two letters sent by Touschek to his parents from Kellinghusen. These letters, as most of the others we have retrieved, are addressed to his father and to his stepmother, since Touschek's mother had died when he was young, and the father had remarried. The letters were written after the war, on June 22 and November 17, 1945, the first of which was received only on October 22, as remarked in a short note under the date. The two letters contain some repetitions, however, as they complement each other, we have opted for publishing here both of them. Some parts of the letters are hard to read and we have inserted question marks when the sense was not clear. Also some references to personal matters have been omitted and indicated with [. . .].

June 22nd, 1945 (letter received by Touschek's parents on October 22nd, 1945)

`Dear parents,`

One of our drivers will leave today to go home to Brünn [the German name of the Czech town Brno] and I hope he will be able to send you this letter.

I have not had news from you for such a long time and I am, obviously, worried about what may have happened during this time. I do not know what is the situation in Vienna, aerial attacks, battles in the city. It will take some time before I will be able to come.

Now a brief account from my side: I wrote you my last letter from Kellinghusen. The next day I left for Hamburg and arrived there by night, during the air raid. The following day, I was taken to prison to Fuhlsbüttel under suspicion of espionage. The first week was terrible, and I was on the verge of committing suicide, in an isolated cell and guarded by the SS. Then Widerøe gave me some relief: cigarettes, the possibility to complete a theoretical work, etc. After 3 weeks, the prison was evacuated and we (200 prisoners) had to set off on foot towards Kiel. There were SS soldiers behind us, in front, and on both sides. Near Hamburg (Langenhorn) I collapsed (I was no longer used to walking). They threw me into the ditch on the side of the road and then shot me. Without success. A bullet went glancing brushing close to my left ear, the other went through the padding of my coat. Since Widerøe had visited me and had told me that the courier carrying the papers for my release was on his way from Berlin, I went to Langehorn Hospital to get bandaged. Of course they imprisoned me again and sent me to Hamburg, from one prison to another. All this lasted about 4 weeks. In the meantime, Widerøe had gone to Norway and nobody seemed to know where I was. I wrote a series of secret messages [to let people know of my situation]. Prof. Lenz would smuggle some food into the prison for me, and finally my working team at the Ministry learned of my existence. A few days before the occupation of Hamburg, Holnack came to get me out of prison, although not quite legally. This was timely, since I would have been shot, in the best case. I then went to Kellinghusen by car and I am still there. In the meantime, I have tried to recover. I can state that this attempt was successful. As an Austrian, I receive 4 times the normal ration and this is already something. I have done the interpreter and now speak fluent English. We want to save the *Strahlentransformator* [the betatron] and it may even be possible. Our name is MW-Research-Association. My plan is to do a PhD in a Northern country, probably Oslo, Widerøe started discussing this with Prof. Hyleraas already during the war. But before I would like to go to Vienna for about 2 months. My life appears more secure now, as I compare it with other's. Anyway, there appear to be all the premises for a good start in the new world. [??]. I have received two letters [...] Another from Sommerfeld, in which he asks about his son, who during my imprisonment lived in my room in Kellinghusen, and who then very stupidly, so to speak, went to Berlin with the last [??] and now nobody knows where he is. The English here are very correct and decent. How is it going with your occupation troops?

P.S. Please, do manage to write to me.

Bruno Touschek's letter to his father dated November 17th, 1945

Dear parents! I was so relieved when I received your letters, one after the other and in inverted order. After all I heard on the Russian zone, especially in the last period I was terribly worried, without the possibility of unfortunately doing anything neither then nor now. In the next days though, a decision will be taken. To make the matter completely clear, I would like to tell you what happened starting from the beginning of March. More or less in that period, I do not remember very well, I must have gone to Hamburg where I felt terribly cold. Relationships with Berlin were not the best: disapproval for my collaboration at the Betatron, many telephone conversations with Widerøe, [...], etc. Widerøe told me that CHF Müller, where the Betatron was moved to, had become unbearable and that he had the intention of moving to Kellinghusen. On the 15th the situation had thus become tragic. We left together and I had a nice room down there. On the morning of the 16th we were still sitting down in the veranda, it was a beautiful spring morning and we were reading the Physical Review in which we had found an article on the Strahlungsdämpfung (an article of two Russians) that later on had received quite a good attention. In the evening I came back home with the truck. The driver did not know the area very well, he drove over a child at Itzehoe who, thanks to God, got only scratched, and along the way two holes burst 10 kilometres from Hamburg. Around midnight I reached Hamburg during the alarm and after the alarm I had another telephone conversation, then I went back to sleep to be waken up at 7.30 in the morning by two gentlemen. I was so sleepy that when they said: ''Secret state police!'' I answered: ''Yes, but at midnight?''. The two, though, were very kind. It took them an hour to search through the mess that my desk[110] was, to search me for hidden firearms and to put everything in my bag. The bag, which was quite heavy, I had to bring it by myself to the Gestapo (15 minutes from Dammtor). They interrogated me for an hour, to tell me in the end that they did not know why they had to arrest me, the order had come from Berlin. I asked them to inform Seifert and the 'assistant', whose name was Kneesch, called him. After Kneesch told me I should not get angry if the tone downstairs was 'rude but sincere', I was then brought in a basement. We sat on a bench, the face towards the wall. The window in the courtyard was open and it was very cold. My neighbour was not ''waterproof'' and was dripping from above and below. After an hour we were brought by tram to Fuhlsbüttel. There the various rites of cleaning and lice searching. I was then brought to the cell where the jews were and where there was a lot of good company. With a certain Waiblinger, who now studies, I am still friends. The only unreasonable thing was that there was no space to sleep, the toilet stank and obviously the people were not in good health. Apart from this, there was practically nothing to eat. The following day was Sunday. The next Monday I was again brought to the Gestapo in a overfull tram wagon, better not discuss the treatment during these transportations. At the Gestapo Seifert, Dr. Widerøe and Dr. Kollath were waiting for me. I boldly made Widerøe understand that I preferred to be imprisoned by myself and he explained to the Criminal Commissioner Windel that they would not have taken the responsibility if I had been put in a cell with the others. Apart from this, the future of the Reich, for better or worse, depended from a research on the influence of the radiation-damping just started by Mr. Touschek. Mr. Touschek should have the right to smoke, read and receive visits. The first week nothing

[110] Touscheks letter calls it "Augian Stables".

came from these concessions. I was confined without a pencil. Widerøe had put a couple of cigarettes in my pockets, but I had no matches. On Friday I wanted to hang myself, and on Saturday, Widerøe came. From then on the situation got better. I had a 'decent' cell on the first floor and Widerøe brought me Heitler's Quantum Theory of Radiation and I started research on radiation-damping. W. never forgot to bring me a pack of cigarettes with written on it the important sign 'Propellent for you'. Apart from the terrible nutrition, the worse thing was to be forced to sit or stand up alternatively all day long. Furthermore, it was horribly cold. After a lot of coming and going which procured some free cigarettes to the SS on guard, I managed to obtain the permission to lay down in my cell, so I stayed horizontal for a whole week with Heitler and Joos under my arm and, in my mouth, a quote from Goethe's ''Götz.''[111] I was treated relatively well, because the frequent visits by important people gave me a certain respect. The VDE wrote me: we hope everything is going well and that you have found the ideal conditions to work in...thinking I was in Kellinghusen. One Wednesday, about April 10th, W. visited me and told me the courier with my pardon papers was coming from Berlin [??] The day after, despite my protesting, I was woken up at five o' clock.

At dawn we met in the corridors. At the beginning, the fact that we should march towards Kiel was only a murmur, but at 10 o'clock it was a fact. I tried to protest again with the SS, especially since I was waiting for my release. I had suffered the whole week of diarrhea, the worst thing that can happen to a prisoner. I was not able to stand. In all 200 of us were deported. We all received a big sack to carry. They were extremely heavy, loaded with books. The people were divided in groups of twos. The whole affair was very discomforting. I definitely broke down in Langenhorn. They made me roll down the trench near the street and then they shot me, one bullet pierced through the padding of my coat, the other one went very near my ear. I waited for the guards to go away. In the meanwhile some people had assembled to see if I was dead or not. I wanted to find the way to phone Seifert and ask him for a car. In the meanwhile my head was hurting me terribly and I managed to go to the hospital of Langenhorn, I needed help. Thanks to Widerøe's message I had no worries about it. But they would have been justified. They brought me to all kinds of prisons for other three weeks, during which I met the state actor Gmelin, now a good acquaintance of mine, and the brother of the mayor of Frankfurt, a certain Kurt Pfeiffer, who had been put into office in Frankfurt by the liberating English armies. The last station was the prison of Altona which -- although I have no musical talent - reminded one of die Fiedermaus operette. From there, Hollnack came to pick me up on the 30th of April. He then explained to me -- after having done nothing for three weeks -- that without him I would have definitely been shot. In any case he then made himself very busy. I went with him to Kellinghusen. Also Kollath and Schumann were there. [There was] Also a group of not very nice people that Hollnack had brought with him to Kellinghusen from various posts of special service. Feeling obligated to Hollnack, I drew an agreement with him. We founded the MV-Research Society. I took the part of stipulating deals with the military regime, for a short period I was an interpreter and I also obtained for our enterprise to be occupied by the T-force, which, in this situation full of looting and vandalism, seemed necessary. After a short time H. started harboring grandiose ambitions.

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[111] The quote is "lick my ass".

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When things were not as he wanted, he started going into publishing news,
into cultural relations, etc. At the end of June, I asked them to end our
collaboration. A long discussion ensued on the subject. We settled for three
months leave. H., who managed to save 200,000[112] from the war, always tends
to enlarge his contribution. The guards call him Kellinghusen's Mussolini.
At the end, I fought with everybody. In late August I went for a trip to
Göttingen [...]. I visit Professor Jensen in Hannover, I meet Dr. Süss at
the University of Göttingen, I am brought in tour as a person who had been
considered dead. Jensen offers me an assistant position and grants that
he will talk to the head engineer in order to assure a position for me.
Same offers in Hamburg. I write a dissertation on the Betatron. A reunion
with the T-force has decided that things should remain a State secret, so
that its use for a thesis is out of the question. I will be able to leave
Kellinghusen only after an Allied commission has decided in regard to the
Betatron. From then on, I am seated in Kellinghusen, practically as a prisoner.
The food is bad, I have a cold, I am, as I was earlier, very badly nourished
and have nothing to dress with. Part of my belongings has been stolen at
the Gestapo, and here there are only useless 'buying stamps'. The German
offices only work for the Nazis and obviously the English do not care for
such low happenings. Of course there are exceptions. The commission should
come in the next days. After that, I will try to obtain some vacation in
Vienna. Please write to me in detail from what you live on at the moment,
what you need, etc. Maybe I can also organize something from here too. Write
soon. Say hello to everyone, Peter etc.
P.S. I wish I were in Vienna already, I cannot wait.
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6 Selected drawings

Bruno Touschek's drawings were a cherished possession of all his friends and colleagues. His ability to draw emerged very early and is clear from the drawings included in the letters to his parents and which we have reproduced in earlier sections. Many of Touschek's drawings have been published in [7], but a large number of additional drawings are among Touschek's documents kept by Touschek's family and are not known. In this section we shall reproduce six drawings of Bruno Touschek. These drawings have never appeared in print and have been retrieved from the documents in possession of the Touschek family. The first two drawings has been extracted from Touschek's letters to his parents, respectively dated April 20, 1942 and January 18, 1944. The others are undated and give us Touschek's keen and incisive eye on academic life of the time.

[112] It is not specified in the text whether the number refers to marks.

Conclusions

In this brief note, we have tried to recall the scientific and human path which led Bruno Touschek to propose and build the first electron-positron storage ring AdA, in 1960, in Frascati, Italy. We also described the role he played in developing the theoretical background for administering high precision radiative corrections to electron-positron experiments and his influence on a generation of young theoretical physicist he trained in the 1960s and early 1970s. This work has utilized existing sources, but also an unpublished and so far unknown series of letters written by Touschek to his parents during the war. Due to the complexity of the material and space restrictions, only a fraction of the content of these letter has been included here. It is our intention to publish separately the full collection of letters and drawings.

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A Chronology of Touschek's life during the war years

In this appendix we present a brief chronology of Bruno Touschek's life during the war years.

1939-1940 : Bruno Touschek attends classes in University of Vienna, passing the relative examinations
May 1940: Bruno Touschek is not allowed anymore to attend the university
1940-1941: from Urban's letter to Amaldi, Bruno Touschek appears to have been working at home or at Urban's home together with other students, studying books borrowed by Urban from the University library, among them Sommerfeld's treatise *Atombaum und Spektrallinien*
Fall 1941: Urban goes to Munich taking Bruno Touschek with him and introducing him to Arnold Sommerfeld, who helps him to find a job in Hamburg and writes letters of introduction to Wilhelm Lenz and Paul Harteck. Urban's letter to Sommerfeld is dated December 1941 and Touschek's letters from Germany to his parents are already from February 1942
March 1942 : Bruno Touschek is in Hamburg, looking for lodgings
Spring-Fall 1942: Bruno Touschek works in Hamburg for a firm developing "drift tubes" and follows courses in Hamburg
September 1942: Rolf Widerøe submits his paper for a 100 MeV betatron to Archiv für Elektrotechnik"
November 1942: Bruno Touschek moves to Berlin and starts working at Löwe Opta, following Max von Laue's courses at Berlin University
Spring 1943: Bruno Touschek working in Berlin reads Rolf Widerøe's paper on the betatron submitted to *Archiv für Elektrotechnik*
Spring–Summer 1943 : Bruno Touschek enters into correspondence with Rolf Widerøe who invites him to join the work on the betatron
August 1943: Rolf Widerøe moves to Hamburg to start work on a 15 MeV betatron financed by the Ministry of Aviation
April 1944: Bruno Touschek moves back to Hamburg to accelerate work on the betatron, but continues to keep his flat in Berlin and keeps traveling between the two cities
Summer 1944: Bruno Touschek travels to Vienna to and from Berlin, and describes this with the "train drawing", shown in one of the figures
March 13th : Touschek writes to his parents from Kellinghusen, where the betatron has been moved.

In the following we present the chronology of events between March 13th and May 1945, extracted from the two letters reproduced in Sect. 5.

March 15th : in Kellinghusen (postwar letters from here on)
March 16th : Touschek and Widerøe are in Kellinghusen, on the veranda, it is a beautiful day; late in the night Touschek reaches Hamburg during an air raid
March 17th : Early in the morning Touschek is arrested, brought to the Gestapo and then to prison
March 19th : Widerøe and Kollath arrive and obtain for him to be in a cell separate from other prisoners
March 23rd : Touschek is desperate and contemplates suicide
March 24th : Widerøe comes visiting
April 10 or 11: Widerøe comes and tells Touschek that papers for his release have been signed
April 12th : Touschek is in march toward the Kiel concentration camp, together with other 200 prisoners; he is shot at and left for dead, after going to a hospital, he is again imprisoned
April 30 : Touschek is set free
May 3rd : The British troops occupy Hamburg

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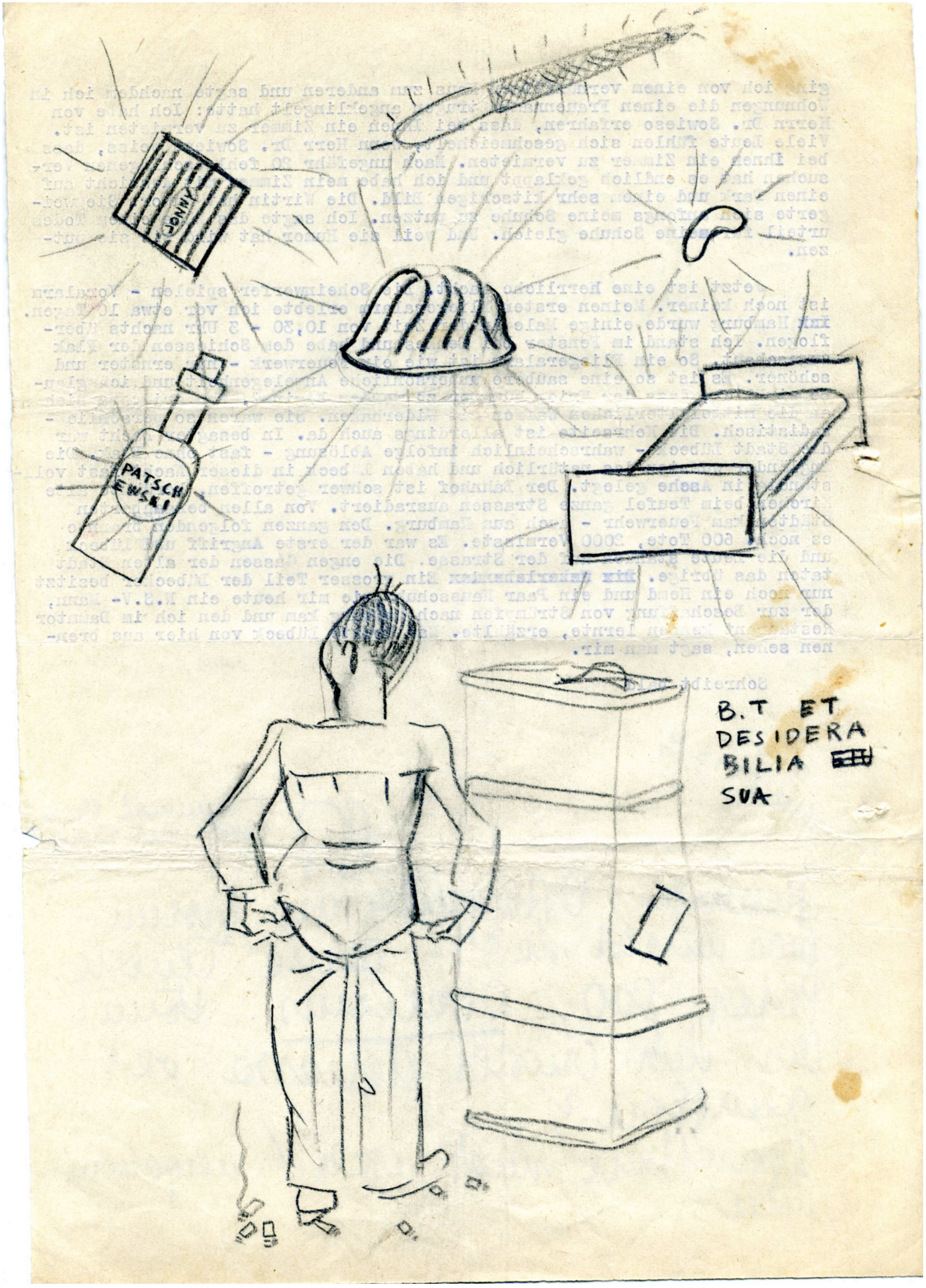

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Fig. 16. This drawing, included in the letter dated April 20, 1942, is entitled *Bruno's desiderabilia.*

Fig. 17. This drawing was included in the letter dated January 18, 1944 and represents a (virtual) offer of gifts for his father's birthday.

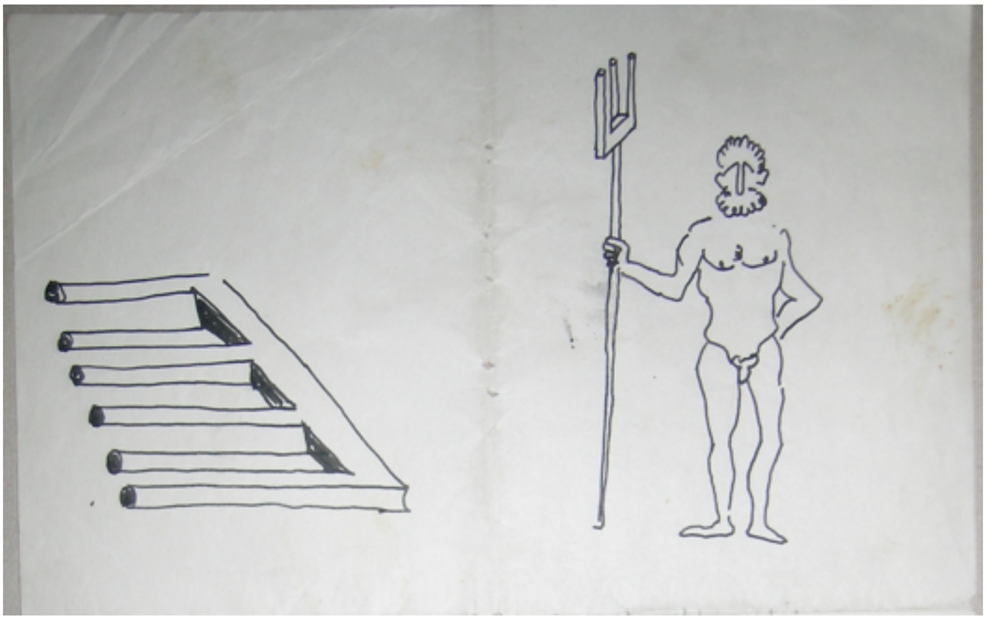

Fig. 18. One of Touschek's many variations on drawing optical illusions. Possible date is in the 1960s.

Fig. 19. Caricatures of colleagues at meetings

Fig. 20. Sarcastic description of a conference meeting, date around 1960.

Fig. 21. Cartoon dated around 1968.