Chapter 2
Bruno Touschek (1921–1978). The Path to Electron-Positron Collisions

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Abstract The 100th anniversary of Bruno Touschek's birth also marks 60 years since the first beams of electrons and positrons circulated in AdA, the first ever matter-antimatter collider, built in Frascati National Laboratories following Touschek's visionary proposal of February 1960. Touschek's path to such idea is briefly outlined, beginning with his early years as a student—first in Vienna and later in Germany—through his first experiences with Rolf Widerøe's betatron and the electron synchrotron accelerator in Glasgow after the war, along with his relationships with the fathers of modern physics in Europe, to his arrival in Italy, where crucial reflections during the 1950s led him to the profound belief that matter-antimatter annihilations should become a primary goal for future physics. Based on these premises, Touschek and his collaborators dared to take on the challenge of realizing what at the time seemed an "unthinkable idea": keep beams of electrons and positron circulating for hours in the vacuum chamber of a storage ring and making them collide.

2.1 A European Scientist

The centennial of Bruno Touschek's birth inaugurates a new phase in the historical studies on one of the most original figures of 20th century physics. Touschek's scientific path is closely intertwined with his personality and of course his life—a life in many respects quite out of the ordinary. Like many of his generation, Touschek went through a dramatic period of the last century, but he also experienced the enthusiasm and excitement of struggling for the reconstruction and revival of European physics after the tragedy of World War II. And indeed, Touschek's life both as a scientist and an intellectual, unfolded across Europe in space and time in different phases during which he had the chance to come in contact with some of the most influential European physicists and more in general with different scientific communities that greatly enriched his cultural background and scientific thought. His mentors were

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the main protagonists of 20th century physics, among the founding fathers of quantum theory and of the new quantum mechanics. Touschek was essentially self-taught until graduation, and yet had the opportunity to interact with many eminent German scientists and to gain practical experience as a theoretical physicist working on the project for the construction of a betatron during the war. Precisely because of his peculiar training as a physicist, who did not follow a standard path, he was able to conquer his own very special scientific style, resulting from the interweaving of his human and scientific vicissitudes against the backdrop of the annexation of Austria to Hitler's Reich, the war years and the early post-war period. He eventually landed in Italy, where his creative potential was able to flourish in contact with a dynamic scientific reality at the reconquest of excellence after the dramatic consequences of Mussolini's racist laws and the war. In Italy, working at the Physics Institute of Sapienza University of Rome and the INFN Frascati National Laboratories, Touschek conceived and built AdA, the first matter-antimatter collider, and in France, at the Laboratoire de l'Accélérateur Linéaire, he finally proved with his Franco-Italian team that the collisions had taken place.

2.2 Intellectual and Family Roots. Childhood and Early Youth in Vienna

Bruno Touschek was born to Camilla Weltmann and Franz Xaver Touschek on February 3rd, 1921, in Vienna, where he spent his childhood and early youth. Between the end of the 19th century and the beginning of the First World War, the Austrian capital was a highly cosmopolitan city and one of the most important centers of scientific advancement. But it was equally a center for the creation of modernity, the cradle for a number of ideas that shaped the whole 20th century and flourished in art, architecture, design, literature, science, philosophy and music. Among other political and artistic movements, the Austrian capital was a home to psychoanalysis, but also to Nazi ideology [1]. At the epicenter of this multifaceted world was the writer and essayist Karl Kraus. His caustic satirical spirit and his cultural engagement in the fundamental ideological issues of his time, had a profound influence on Touschek's intellectual formation.

Touschek's own family was actively involved in this scenario. His mother Camilla Weltmann and his aunt Ella—and Ella's own husband, the architect Josef Margold—were active in the circle of the Wiener Werkstätte, the association evolving from the Vienna Secession movement, founded by Josef Hoffmann and Koloman Moser as an alliance of artists, architects, designers and artisans that pioneered modern design and eventually influenced the Bauhaus movement as well as the Art Deco style. His maternal uncle Oskar was also an important reference figure for Bruno in his early years. He committed suicide in 1933, while Bruno's mother, Camilla, had already died, when he was only 9 years old (Fig. 2.1).

Fig. 2.1 Left: Bruno as a child with his mother Camilla Weltmann. Right: “Russia supreme war council”, drawing made by Touschek when he had just turned 6 years old (title and date on the back: “Obersterkriegsrat Russland”, March 31, 1927). *Credit* Francis Touschek

Touschek grew up in such amazing cauldron of great avant-garde cultural movements. His precocious talent for drawing, was influenced by the innovative expressionism of Egon Schiele and the famous psychological portraits of Oskar Kokoschka, artists who challenged established ideals of ‘beauty’ and shaped new ways to look at art seeking novel subjects for representation in their work. The style of Touschek’s own drawings—well-known among friends and colleagues—testifies the persistence during his whole life of such strong and lively bonds with the rich cultural and intellectual world of his home town, that subtly blended in his personal and very original style.

2.3 University Studies in Vienna After the *Anschluss*

He had just turned seventeen years old on March 15, 1938, when Hitler announced the *Anschluss*, in Heiden Square, in front of an oceanic crowd. Due to his Jewish origin on the maternal side, the annexation of Austria into Nazi Germany completely turned his life upside down and dramatically affected his future forever. At that age, he was deeply aware of and intensely suffered in experiencing the dramatic events that were happening around him.

He was no longer able to attend classes as a regular student at school, but in 1939, after taking his Matura, his final examination, he enrolled in physics at the University of Vienna whose tradition included scientists such as Ludwig Boltzmann and Ernst Mach, who had influenced the turn-of-the century new generation of physicists, such as Lise Meitner and Paul Ehrenfest. Pauli himself, born in 1900, was raised among the intellectual elite of Vienna and Ernst Mach had been his godfather and first mentor. However, in June 1941, Touschek was expelled from the University for racial and political reasons and could only continue his studies privately, helped by

Fig. 2.2 Bruno Touschek's passport photo at 18 years old. *Credit* Francis Touschek

Paul Urban, who had received his Ph.D. in theoretical physics under the supervision of Hans Thirring, and had been his assistant at the Institute for Theoretical Physics at the University of Vienna (Fig. 2.2).[1]

2.4 Moving to Germany Protected by Arnold Sommerfeld

Paul Urban put Touschek in contact with Arnold Sommerfeld, who had educated and mentored a whole generation of young physicists and students (notably Werner Heisenberg and Wolfgang Pauli) who had a key role in the new era of theoretical physics. Sommerfeld had also openly supported Einstein and his work when the latter had been attacked by Philipp Lenard and Johannes Stark, who labeled relativity and quantum mechanics as *Jewish Physics*. For defending his Jewish colleagues Sommerfeld was forced into retirement when the Nazis came to power in 1933. Touschek had carefully studied Sommerfeld's classical treatise *Atombau und Spektrallinien*, finding some small errors. The beginning of their correspondence dates back to that time. In the years following the advent of the Nazi regime, Sommerfeld became increasingly concerned about the fate of physics in Germany—in particular theoretical physics. With his well known ability in the discovery of talents, he saw in such a gifted student a promise for the future. By the early 1940s, German physics had already lost so many brilliant scientists and there were no longer any Jewish physics professors left after the Nuremberg Laws. Somerfeld helped Touschek to find a work in Hamburg in an electronic firm led by Günther Jobst, a former student of his. In early 1942 Touschek abandoned Vienna and with great courage continued to pursue his passion for physics during the war years. Despite still being unable to

[1] For further details on Touschek's life and science see Giulia Pancheri's contribution in these proceedings and her volume *Bruno Touschek's Extraordinary Journey—from death-rays to antimatter* (Springer 2022) [3].

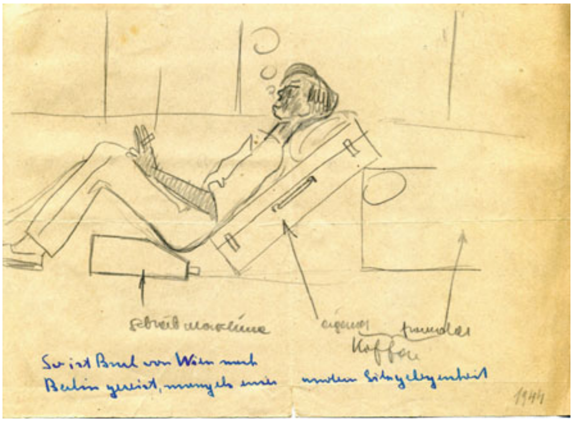

Fig. 2.3 Bruno Touschek's drawing in a letter written to his father on September 11, 1944. The drawing depicts one of his journeys from Vienna to Berlin and the makeshift seat he arranged by means of his own and another suitcase and his faithful typewriter that he always carried with him. *Credit* Francis Touschek

attend classes as a regular student, he continued his studies in Germany protected by Sommerfeld's colleagues and friends in Hamburg and later in Berlin, and at the same time worked to support himself. Hamburg University had risen to international fame during the era of the Weimar Republic thanks to its outstanding scholars, such as Ernst Cassirer, Erwin Panofsky, Otto Stern. As a Jew, after Nazi's seizure of power in 1933, Stern had been forced to resign from his post, similarly to many other colleagues, notably Panofsky, who was Pauli's and Einstein's friend. Both Panofsky and Stern found refuge in the United States, and the latter resided there when he was awarded the 1943 Nobel Prize in Physics. Panofsky's younger son, Wolfgang, became a renowned physicist and later played a relevant role in the art of particle accelerators. In the 1950s, his path eventually crossed Touschek's own way to new physics with colliding beams.

In Hamburg, Touschek established a strong relationship with Wilhelm Lenz (who had been Sommerfeld's student and his assistant in Munich), and was Director of the Institute of Theoretical Physics. Lenz had trained Ernst Ising and his assistants had included Pascual Jordan and Wolfgang Pauli. In Hamburg Touschek also became friends with Hans Jensen and Paul Harteck (of Austrian origin), both members of the *Uranium Club*, the German nuclear project led by Werner Heisenberg since 1942.

In late 1942, Touschek moved to Berlin and began to work at the Löwe Opta Radio company. In Berlin and Hamburg, Touschek experienced the heavy bombing raids and in particular the horror of firebombing of which he gave a chilling but very lucid and detailed description in his letters to his father and stepmother, often enriched with vivid drawings to complement the rich account of his daily life. This large group of letters constitutes a precious and irreplaceable documentation, a direct record of Touschek's life starting from 1939, when he was forced to abandon his native city (Fig. 2.3).

In Berlin he met Werner Heisenberg, Karl von Weizsäcker and Max von Laue, who showed great interest in his studies. Planck himself was still alive. Touschek followed their lessons and participated in seminars. But in 1944, when bombing began to menace the Max Planck Institute for Physics in Dahlem, Heisenberg and the others moved to Hechingen, in southern Germany, where they continued to work on the German nuclear project.

Those were still the months of Hitler's conquest of Europe; German troops had even occupied Paris in 1940. But since 1942, as the war situation worsened for Germany, Hermann Göring, high commander of the Air Force, fostered great hopes in the saving power of wonder weapons, the so called *Wunderwaffen*, which actually were also part of the propaganda disseminated by the government to keep up the morale of the population and instill confidence in the war resources of the Reich [4].

2.5 Building a 15-MeV Betatron with Rolf Widerøe

In early 1943, Touschek read an article submitted to the journal *Archiv für Elektrotechnik* by the Norwegian electric engineer Rolf Widerøe and describing a project for a betatron, a new kind of accelerator built by Donald Kerst in US, inspired by Widerøe's own ideas of several years before [5].

Widerøe's article entitled *Der Strahlentransformator*, was actually prepared for publication, but it was never included in the volume 37, issue 8, of the *Archiv für Elektrotechnik*. A copy is preserved in the Max Planck Archives in Berlin, together with a second typewritten manuscript with plans for a more powerful betatron. Following Touschek's indication of the interest of the proposal, the betatron immediately became a secret project of the Luftwaffe, as the military expected it would be able to produce powerful death rays to be used against enemy aircraft during air battles.[2] The possibility of producing high-energy X-rays for such aims was of course immediately set aside on scientific grounds, but nevertheless resulted in funding the construction of a 15-MeV betatron by the Reich Aviation Ministry, in view of a 100- and even 200-MeV machine.

Touschek was involved in this project as a theoretician. For the first time he found himself facing as a physicist both the challenge and the responsibility of the theoretical part of a relevant project, in addition to having to deal with a completely new field. This implied understanding what happens to charged particles circulating in an accelerator such as the betatron, subjected to electric and magnetic fields, as well as studying a series of phenomena that only in those years began to be tackled. This involvement temporarily saved him from being deported to forced labor by the Todt Organization, the OT, which he often mentioned in his letters home. This would have meant to be treated as a slave, doing extremely hard work in terrible conditions, which were often impossible to survive.

However, in the meantime, the Gestapo continued to keep an eye on him. In mid-March 1945, after having helped to move the completed betatron away from Hamburg to escape the advance of Russian troops, Touschek travelled back to Hamburg, where

[2] See B.I.O.S. Final Report No. 201, Visit to C.H.F. Müller A.G., Hamburg, p. 3. https://www.cdvandt.org/bios-201.htm.

something terrible happened, as he wrote in the first letter to his father after the war: "*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?' [...].* Despite the dramatic vicissitudes he had experienced, which only after many months he was able to tell his loved ones, he managed to minimize them in their eyes with the power of his extraordinary sense of humor.

2.6 Surviving Gestapo Captivity and a Death March to Kiel

During the weeks following his arrest, Touschek went through a horrible experience, languishing in a Gestapo prison and being shot twice during a march to the concentration camp of Kiel since he had fallen to the ground having a very high fever and under the weight of a large quantity of books that the prisoners had been forced to carry. Around 200.000 people died during such so-called death marches. Orders were to shoot the weakest prisoners and all those lagging behind or attempting to flee [6]. By that time, his maternal grandmother had already died at the concentration camp of Theresienstadt.

After being shot, Touschek was left there on the side of the street, but he was still alive and was imprisoned again and bounced around between different prisons until he was finally released a few days before the end of the war on the initiative of the

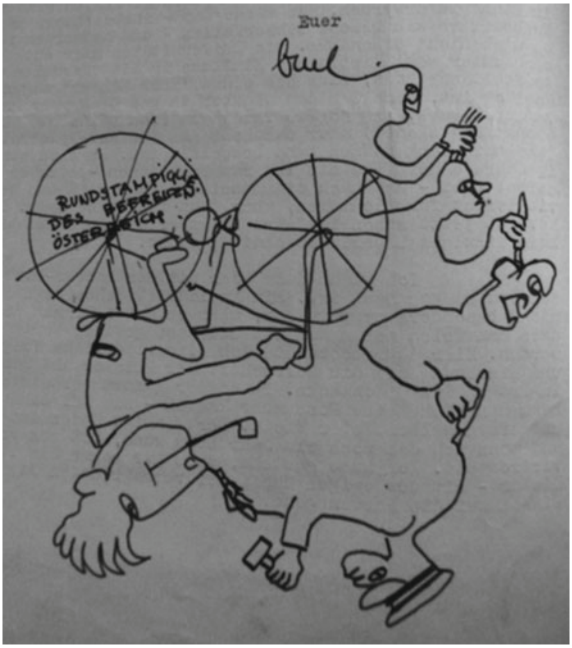

Fig. 2.4 "Round stamp of liberated Austria", drawing in a letter written to his father in March 1950. The drawing is created as a graphic extension of the family nickname "Burl", his usual signature in letters to the family. *Credit* Francis Touschek

betatron team. Otherwise, he would have certainly been shot by the German troops retreating during the last hours of the war (Fig. 2.4).

2.7 In Göttingen with Heisenberg and Other Members of the *Uranium Club*

He miraculously survived such dreadful events and after the war, he finally obtained his degree in Physics at the University of Göttingen with a dissertation on the theory of the betatron based on his reports to British Intelligence,[3] which testify how crucial were his participation and his role as a theoretical physicist in Widerøe's betatron project.[4] In Göttingen, Touschek came in contact with many members of the *Uranium Club* who had been released from their internment in UK at the beginning of 1946. The integrity of scientists such as Max Planck, Otto Hahn, and Max von Laue had never been in doubt. With their help and the support of the British authorities it became possible to initiate the reconstruction of fundamental scientific activity in Germany from the ashes and destruction of Nazi's regime. In the meantime, as Touschek wrote to Sommerfeld, he made "a bit of neutrino theory", "a bit of radiation damping," as well as "betatron calculations".[5] For some time, he was Werner Heisenberg's assistant at the Max Planck Institute for Physics in Göttingen, continuing his formation under the influence of the great German theoretical school.[6]

2.8 In Glasgow (1947–1952): The Making of a Theoretical Physicist

On the whole, such a difficult period in his life turned out to be a major step along the way to the first matter-antimatter collider. Despite having lost several years of his

[3] Copies of such reports on the theory of the betatron written by Touschek (Zur Theorie der 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) can be found in Rolf Widerøe's papers at the Eidgenossischen Technischen Hochschule (ETH) in Zurich.

[4] Touschek's contribution is clearly acknowledged also in a detailed British Intelligence Objective Sub-Committee (B.I.O.S.) report on *European Electron Induction Accelerators* prepared in October 1945 by the U.S. Naval Technical Mission in Europe: "In collaboration with the design work of Wideroe, 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. Further theoretical work has been done by Touschek on the starting of electrons in the accelerator" (Miscellaneous Report No. 77, Technical Report No. 331–345 prepared by H. F. Kaiser. https://www.cdvandt.org/bios-miscell-77.htm, p. 6).

[5] Arnold Sommerfeld's papers, Archives Deutsches Museum, Munich.

[6] On this period of Touschek's life see [7–9].

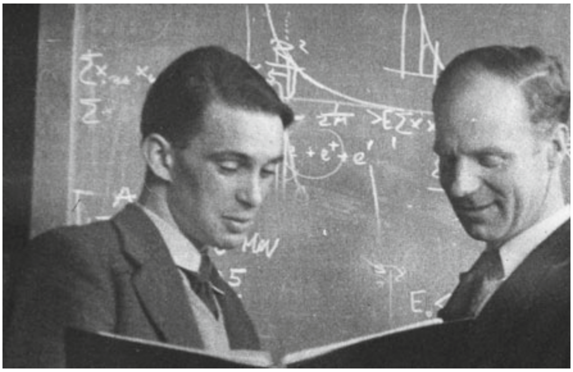

Fig. 2.5 Bruno Touschek with the physicist Samuel C. Curran, his colleague at Glasgow University. *Credit* Francis Touschek

youth, he re-emerged from the war and early-post war years as one of the first physicists in Europe endowed with a unique expertise about the theory and functioning of accelerators. And so, in early 1947, the British Intelligence arranged for his transfer to Glasgow University, in the Physics Department directed by Philip Dee, where they had built a 30-MeV electron synchrotron as a testing ground for the planned 300-MeV machine. While being involved in theoretical studies and in the building of the 300-MeV electron synchrotron (Fig. 2.5), Touschek was also consulted as a betatron expert by other research centers in UK. In 1949 Touschek was awarded a Ph.D. in Physics with a dissertation entitled *Collisions between electrons and nuclei*. His external supervisor was Rudolf Peierls, who had studied under Sommerfeld and Heisenberg, and had been Pauli's assistant in Zurich. While in UK with a post-doc grant, Peierls had decided not to return home after Hitler's rise to power in 1933 because of his Jewish background.

In UK Touschek came also in contact with Max Born, one of the fathers of the new quantum mechanics, and collaborated with him writing an appendix for a new edition of Born's book *Atomic Physics*. Born himself, being Jewish, had been suspended from his professorship at the University of Göttingen in 1933 and had moved to UK. Physicists such as Heisenberg, Pascual Jordan, Pauli, Edward Teller, Eugene Wigner, Viktor Weisskopf, had been his Ph.D. students or assistants. Born received the Nobel Prize in 1954.

In Glasgow, Touschek became a full-fledged theoretical physicist. He did theoretical work on the phenomenology of meson physics at accelerators, and began to work in quantum field theory. He thus experienced the initial phase of particle physics with accelerators, the transition from cosmic rays to more systematic studies with artificial beams of particles as one can see from Touschek's published works between 1948 and 1951.[7]

At that time he collaborated with Walter Thirring on the article *A covariant formulation of the Block–Nordsieck method* [12]. They both shared a growing interest in quantum electrodynamics which was becoming a hot topic and led Touschek to

[7] See [10] for a complete list of Touschek's works.

a friendship with the well-known Italian physicist Bruno Ferretti, who was in UK around 1948, and who eventually became the intermediary for Touschek's transfer to Italy.

As we know from letters to his father and especially to Arnold Sommerfeld, Touschek soon began to feel that in Glasgow he was rather far from the mainstream of theoretical physics. He was unhappy, and soon after being awarded the Ph.D., he felt that it was time to consider other possible positions in Europe. He missed Germany, and was particularly looking forward to working with Heisenberg again, as he wrote to Sommerfeld in October 1950: "*I have found that I am more comfortable in Germany and Austria than in Scotland, and that I have learned more in Göttingen in a month than in Glasgow in a year [...] If Professor Heisenberg comes to Munich and wants me, then I want him too, if it can be done somehow financially*.[8]

In the very early 1950s, he shared lively discussions on quantum field theory with Bruno Ferretti, from whom he also heard about the great plans and expectations related to the rebuilding and relaunching of Italian physics, after the disaster of World War II. Both agreed that Touschek would obtain a leave of absence to be spent in Italy, a country he knew since his childhood, when he visited his second maternal aunt Ada, married with an Italian. In fall of the following year he wrote to his father: "*I have applied for a job in Rome [...] Only masochists can live in England in the long run [...]*".[9]

2.9 Participating in the Reconstruction and Revival of Italian Physics

Like Heisenberg in Germany, Patrick Blackett in UK, Pierre Auger in France—and similarly to other physicists who had experienced the flowering of European physics before the war—Edoardo Amaldi in Italy was deeply frustrated by the passage of leadership from Europe to the United States. Physics in Rome had a long-standing tradition that began immediately after the unification of Italy. The new Institute of Physics at Sapienza University, inaugurated in Via Panisperna in 1881 with first director Pietro Blaserna, who had studied physics in Vienna with Andreas von Ettingshausen, was the most modern in Italy for its research laboratories and for the quality of teaching [13]. Thanks to its second director, Orso Mario Corbino, the first chair of Theoretical Physics was established and Enrico Fermi, with his friend and collaborator Franco Rasetti, an excellent experimentalist, since 1927 opened the way to modern physics in Italy. While Fermi's group in Rome was making its well-known major contributions to nuclear physics, in Florence Bruno Rossi and his colleagues, which included Gilberto Bernardini, Giulio Racah, and Daria Bocciarelli were building a further novel research tradition which for several years would be a well established expertise of Italian physics: the study of cosmic rays.

8 Arnold Sommerfeld's papers, Archives Deutsches Museum, Munich.

9 On Touschek's stay in Glasgow in the years 1947–1952 see [11].

In 1937 the Physics Institute moved from via Panisperna to the new campus of Sapienza University, in the exemplary rationalist building designed by architect Giuseppe Pagano and named after Guglielmo Marconi. Soon after, in 1938, the Roman group definitely disbanded when Fermi decided to move to US and did not come back after being awarded the Nobel Prize. Bruno Rossi, being of Jewish family, was expelled from the Institute in Padua, which he directed—and whose design and construction he had personally supervised—and eventually emigrated to US.

The Italian physics community—and not only—was decimated by the racist policies implemented by Mussolini's fascist government, and deprived of some of its most influential and prestigious members. With them, many others left Italy because of political or racial reasons. After the isolation of wartime, Italian physicists were left with the difficult task of relaunching the field on a new basis, in line with the latest developments but at the same time taking into account the difficult economic situation of the country, half-destroyed by the consequences of the conflict. Edoardo Amaldi and Gilberto Bernardini, heirs of the fathers of modern physics in Italy and bridging that glorious tradition over the war years, initiated an intensive program for the revival of physics in the country and in parallel began promoting an international strategy to relaunch physical sciences in Europe. Amaldi became a key figure in the birth of CERN and the European Space Agency, and Bernardini was CERN'S first Director of Research and first president of the European Physical Society, of which he had strongly advocated the foundation.

Deeply aware of Touschek's potential, which was particularly suited to such ambitious plans, Edoardo Amaldi invited him officially in Rome with an INFN contract.[10]

At the end of 1952, when Touschek arrived in Italy, the National Institute for Nuclear Physics had just been founded with first president Bernardini and Italian physicists were deciding to establish a national laboratory for high energy physics in order to host an electron synchrotron, a new-generation machine they had planned to build as a powerful tool for elementary particle physics. The direction of the project was given to the 33-year-old Giorgio Salvini. After having been for many years at the frontier of nuclear and cosmic-ray research, Italy would have been able to regain a prominent international position, in particular in the sub-nuclear realm. And indeed, Touschek's unique expertise found a very fertile ground and turned out to be destined to have a profound influence on the future of this field, both theoretically and experimentally (Fig. 2.6).

[10] As emphasized by his son Francis, Touschek had always a special relationship with Amaldi, who showed his affection and esteem by writing with great commitment an accurate biography after Touschek's death [10].

Fig. 2.6 Left: Bruno Touschek with Edoardo Amaldi in the 1950s. Right: Touschek's portrait of Giorgio Salvini, director of Frascati National Laboratories. *Credit* E. Amaldi Archives, Physics Department, Sapienza University, Rome; Francis Touschek

2.10 Towards Matter-Antimatter Physics

During the 1950s, Touschek further evolved as a theoretician, giving relevant contributions to the study of discrete symmetries in particle physics, time reversal and neutrino physics also collaborating with several Italian physicists. Let me note in passing that, during the war, we know from the correspondence that he studied Eugene Wigner's book *Group Theory and its Application to the Quantum Mechanics of Atomic Spectra* (published for the first time in 1931) at a time when there wasn't great interest in the subject. But he was aware of its importance, and commented in a letter that it was a kind of "treasure" that he would put aside for later times…

In the 1950s, Touschek had a scientific correspondence with Pauli, whose interests were since some time centered on quantum field theory—and had already resulted in two fundamental pillars of the theory: the spin-statistics theorem and the CPT theorem. The exchange of letter intensified between 1957 and 1958. At that time, the shocking discovery of Parity violation in weak interactions was increasing interest in the discrete symmetry operations, a topic which both actually discussed since 1954. Pauli and Touschek also wrote a joint paper, published in 1959 as a contribution to the *International School of Physics "Enrico Fermi"* (8th Course: "Mathematical problems of the quantum theory of particles and fields") and which appeared only when Pauli had already passed away, in December 1958 [14]. After the funeral, Touschek wrote in a letter to his father: "*Without him, for me physics is only half interesting* […]".

Nevertheless, all this was instrumental in preparing his mind for further crucial reflections (Fig. 2.7).

Fig. 2.7 Left: Bruno Touschek with Tsung Dao Lee and Wolfgang Pauli in Venice at the International Conference on *Mesons and recently discovered particles* in September 1957. Right: Touschek's joking portrait of T. D. Lee alluding to the recent discovery of parity violation, widely discussed during the conference. *Credit* Francis Touschek

2.11 Colliding Beams in the 1950s: e^-e^- versus e^+e^-

During the 1950s, while being actively involved in the life of the Italian scientific community, brilliantly integrated into such lively academic and scientific environment, Touschek closely experienced the birth and development of Frascati National Laboratories that had been established to host the brand new accelerator. Towards the end of 1959, Touschek was around in the Labs directed by Giorgio Salvini, where the 1100 MeV electron synchrotron had just gone on line. Touschek had frequent conversations with Carlo Bernardini on the research perspectives: "*Bruno was continuously exploding in his picturesque Austro-Italian, being rather unsatisfied with the experimental opportunities. He insisted that experiments had to be clean in channels with very definite quantum numbers, thus excluding the overcrowded proton reactions. Electrons appeared to him as 'gentle probes'*" [15, p. 8]. In Touschek's own words, "*On hitting their target [...] a beam of protons loses its identity [...] Protons are a rich source of events, which are difficult to interpret because the witnesses are too much involved. Electrons peering gently at their targets rarely produce spectacular events, but what they produce can be more easily interpreted*".[11]

Since the early 1950s, an extraordinary progress in high-energy physics was mainly due to the availability of large proton accelerators such as the Cosmotron (3 GeV, 1952, Brookhaven), the Bevatron (6.2 GeV, 1954, Berkeley), and the CERN Proton-Synchrotron (28 GeV, 1959, Geneva).

On the other hand, when it started to work the Frascati machine was one of the three biggest of its kind in the world, the other two were in the USA, at Cornell and at

[11] B. Touschek, *Ada and Adone are storage rings* (incomplete manuscript, Bruno Touschek Archive, Physics Department, Sapienza University of Rome, from now on B. T. A., Folder 11, 3.92.4, p. 5).

Caltech. "*That the machine which would bring Italy to a level with international and in particular U.S. high energy physics should be an electron accelerator*—recalled Bruno Touschek later—*was a courageous choice if confronted with a general tendency of physicists who at the time were bent on producing proton accelerators*."[12] "*At the same time, however*—Touschek further remarked—*new preoccupations arose. All over the world newer and bigger machines were being built and planned and it was felt that if Frascati wanted to keep abreast something big and new had to be planned*."[13]

Since the second half of the 1950s, US physicists had been proposing to exploit the colliding beam technique to obtain a larger center-of-mass energy and to carry out high-precision experiments to test the predictions of QED, in particular to investigate "the breakdown of electrodynamics" [15, p. 4]. In parallel, also Gersh Budker with his team in USSR was planning an e^-e^- experiment, Vep-1, apparently also discussing the interest of e^+e^- [16, 17]. Thus, at the end of the 1950s, the storage-ring and the colliding beam ideas were not new.[14]

As recalled by Touschek himself, "*The interest in storage rings at Frascati was started by a visit of Dr. Panofsky in the autumn of 1959*" [19]. In fall 1959, Pief Panofsky, who at the time, was already planning the future 2-Mile accelerator at Stanford, gave a seminar in Rome presenting the US Princeton-Stanford e^-e^- project. Raul Gatto and Nicola Cabibbo, who were both present, well remembered how Touschek immediately reacted proposing a different idea, based on quite different scientific aims, involving the physics of particles and antiparticles: "*It was after the seminar that Bruno Touschek came up with the remark that an e^+e^- machine could be realized in a single ring, 'because of the CTP theorem'* [...]" [20, p. 219]. To support his view on scientific grounds, "*Bruno kept insisting on CPT invariance, which would grant the same orbit for electrons and positrons inside the ring!*"[15]

We also have Touschek's own recollections about the late 1950s, the years ushering the transition to a new phase of his scientific adventure: "*At the time I felt rather exhausted from an overdose of work which I had been trying to perform in the most abstract field of theoretical research: the discussion of symmetries which had been opened up by the discovery of the breakdown of one of them, parity, by Lee and Yang. I therefore wanted to get my feet out of the clouds and onto the ground again, touch things (provided there was no high tension on them) and take them apart and get back to what I thought I really understood: elementary physics [...]*".[16]

[12] B. Touschek, *AdA and Adone are storage rings* (manuscript, B. T. A, Folder 11, 3.92.4, p. 4).

[13] B. Touschek, *A Brief Outline of the Story of AdA* (manuscript, B. T. A., Folder 11, 3.92.5, p. 3).

[14] See [18] for a discussion on related US projects during the 1950s.

[15] R. Gatto, personal communication, January 15, 2004.

[16] B. Touschek, *AdA and Adone are storage rings*, manuscript, B.T.A., Box 11, Folder 3.92.4, p. 7.

2.12 From CPT to AdA, the First Particle-Antiparticle Collider

Then, in February 1960, during a meeting in Frascati Touschek surprised everybody proposing to go far beyond experiments with gamma beams obtained by hitting electrons against a fixed target inside the synchrotron, or even experiments such as those US physicists were scheduling at Stanford with two colliding beams of electrons stored in two tangent rings.[17]

According to Touschek, what would really be worth exploring, instead, was the physics of electron-positron annihilations, which would allow *to open a channel into the hadronic world through the quantum numbers of* e^+e^-. He tried to convince Giorgio Salvini, director of the National Laboratories, to re-convert the electron-synchrotron—that had just gone into operation—into an electron-positron collider. During the discussion that followed, Giorgio Ghigo suggested to build a small dedicated machine in order to perform the experiment proposed by Touschek.[18]

The following day, Touschek started to make calculations on a new notebook, which he named "SR", for Storage Ring, since it was clear that the beam-storage problem would be the most serious one, as he himself recalled some time later: "*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*."[19]

During a seminar held the following March 7, 1960, Touschek emphasized the creative character of e^+e^- collisions, i.e. the possibility of a complete transformation of the collision energy in the creation of new particles, and this through a channel with well-defined quantum numbers—those of a photon—and proposed as an example muon and pion pairs.

The colliding beam technique, which other physicists were planning to exploit both in USA and USSR—basically to obtain a larger center-of-mass energy or to perform high-precision experiments to test the predictions of QED—was definitely moving towards a conceptually novel stage. Because of the CPT symmetry, insisted Touschek, electrons and positron could circulate in the same orbit, in opposite directions, and eventually collide: "*One of the leading motivations for planning* e^+e^- *colliding beam experiments (rather than* e^-e^- *or* $p-p$*) was that in such an experiment one could 'observe' the virtual time-like photon [...]*"[20]

As recalled by Nicola Cabibbo, "*F. Calogero, R. Gatto. C. Zemachs, L. Brown (the two were spending their sabbatical in Rome) and myself rushed to compute the relevant cross-sections*" [20, p. 2].

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[17] For a list of Kerst's, O'Neill's et al. works on the e^-e^- storage ring idea and related colliding beams project see [21, footnote 1].

[18] See preliminary draft of his proposal: B. Touschek, "Proposta d'esperienza", two manuscript pages, B.T.A., Box 11, Folder 3.87.

[19] 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. T. A., Box 11, Folder 3.92.5, p. 8).

[20] B. Touschek, *The time-like photon* (manuscript, B. T. A., Box 11, Folder 3.92.9, p. 1).

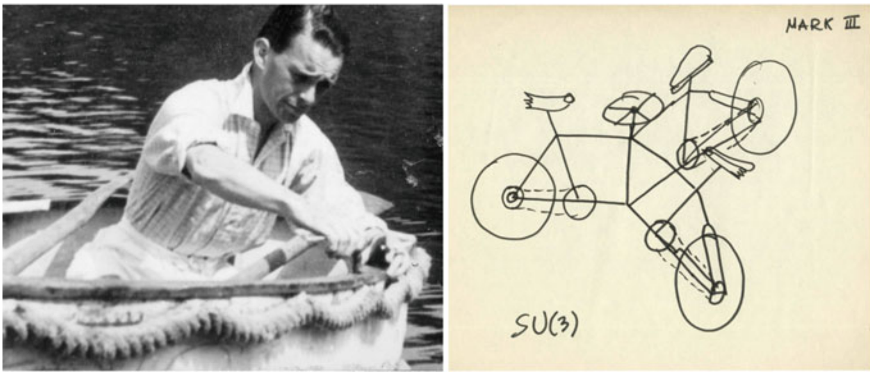

Fig. 2.8 Left: Bruno Touschek on his boat on the Lake of Albano. Right: Touschek's drawing, part of the famous series of his surreal bicycles. *Credit* Francis Touschek

Carlo Rubbia has well expressed such conceptual leap: "*[...] in his mind electron-positron collisions were nothing else than the way of realizing in practice the idea of symmetry between matter and antimatter, in the deep sense of the Dirac equation [...] His boundless enthusiasm for particle-antiparticle collisions was dominated by a sense of perfect and intellectual esthetics...*" [22, p. 59].

The response of the Laboratory was enthusiastic. The project was fully approved and immediately funded (Fig. 2.8).

2.13 The Garden of Eden of Electron-Positron Annihilations

Following his challenging ideas—based on his firm belief in CPT and QED—the first matter antimatter collider AdA (for 'Anello di Accumulazione', Storage Ring), a 4-m perimeter ring suited for electrons and positrons of up to 250 MeV, was built. It inaugurated a brand-new research line at Frascati National Laboratories, heralding a new era in high-energy physics. The team led by Touschek, including Carlo Bernardini, Giorgio Ghigo, Gianfranco Corazza, Ruggero Querzoli and Giuseppe Di Giugno, was able already in February 1961 to observe the light signal from a single circulating electron after its capture in the ring as a pulse in the phototube output, or even as a white-bluish spot that could be seen with the naked eye through a small porthole. Electrons lived for 30 or 40 hours thanks to an unprecedented vacuum of 10^{10} torr, obtained by Corazza, a leader in the field of vacuum technology. In parallel, together with Raul Gatto, Nicola Cabibbo—who had graduated in 1958 with Touschek as supervisor—fully explored the annihilation processes of interest that were presented in their a seminal paper *Electron-Positron Colliding Beam Experiments*, universally known as the 'Bible' in Frascati circles [23]. As recalled by Cabibbo, "*The result of* *this explorative work confirmed beyond the wildest dreams the intuitions of Bruno Touschek*". And emphasized how, "*While doing this work we had the exhilarating experience of expanding into a vacuum: for a few years the only theoretical papers on the physics of e^+e^- were those issuing out of Rome or in Frascati*" [20, p. 221].

2.14 AdA in Orsay, at LAL

In Orsay, at the Laboratoire de l'Accélérateur Linéaire, where AdA was moved in 1962 to benefit from the Linac high particle injection rates, Touschek and his team, now including Pierre Marin and Jacques Haïssinski, were able to demonstrate that the two beams had actually collided, through the observation of the single bremsstrahlung as a monitoring reaction. At the time, the overlapping of the two beams was often put in doubt, as Carlo Bernardini repeatedly recalled: "*How can you be sure that electrons and positrons will meet?*" To such a question Touschek invariably replied: "*Obviously, TCP theorem! Actually, CP is enough!*" [24, p. 170]. This epochal achievement of the Franco-Italian collaboration definitely proved the feasibility of this type of machine [25]. They also discovered an unexpected effect, a loss of particles from the stored beams reducing their lifetime, whose origin was immediately explained by Touschek as an intra-bunch scattering. But luckily, it turned out that the so-called Touschek effect scales sharply with energy and does not seriously affect more powerful colliders [26].[21]

In the meantime, the French started their own e^+e^- project, the collider ACO [29].

2.15 1960s–1970s: ADONE and the Formation of a Theoretical School in Rome and Frascati

In November 1960, even before AdA had showed the feasibility of electron-positron collisions, opening the way to higher energy and luminosity, Touschek prepared a draft plan for a bigger and more powerful storage ring for electrons and positrons, ADONE.[22] The official proposal was presented in January 1961 [30].

ADONE (1.5 GeV per beam, 105 m in circumference), which became operational in 1969, eventually discovered the multi hadron production making electron-positron physics a field of major interest, further encouraging the construction of a large family of high-energy colliders all over the world where new types of elementary constituents of matter were detected. In 1974, ADONE confirmed the existence of the J/ψ, a bound state of a charm quark and a charm anti-quark, discovered at

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[21] For a reconstruction of the birth and development of the Franco–Italian collaboration see [27, 28].

[22] *ADONE—a draft proposal for a colliding beam experiment*, typescript, B. T. A., Box 12, Folder 3.89.

Fig. 2.9 Bruno Touschek with his dog Lola. *Credit* Francis Touschek

the Brookhaven National Laboratory and at the Stanford Linear Accelerator Center with the e^+e^- collider SPEAR. It was the first breakthrough discovery of the colliding beam technique and the first firm experimental evidence for the charm quark—establishing the quark model as a credible description of nature—for which Samuel Ting and Burton Richter were awarded the 1976 Nobel Prize in Physics.[23] As Touschek had predicted, e^+e^- physics was showing its intrinsic simplicity and power.

With AdA and ADONE Touschek created a brand new, major research line at Frascati Laboratories and made a further fundamental contribution with the formation of a theoretical school in Rome and Frascati. Touschek, who was particularly valued also as an extremely brilliant, fascinating and inspiring teacher,[24] was invited by Luigi Radicati to give lessons at the Specialization School of the Scuola Normale Superiore in Pisa.[25] In 1972 he was elected as Foreign Member of the Accademia Nazionale dei Lincei, while in 1975 he was awarded the prestigious Matteucci Medal by the Italian National Academy of Sciences. A glance at the list of distinguished physicists to whom the Prize has been awarded since 1870 places Touschek at the highest level of world physics (Fig. 2.9).

[23] See contributions by Pancheri, Pellegrini and Greco in these Proceedings.

[24] See contribution by G. Rossi in these Proceedings.

[25] In an interview Luigi Radicati recalled his friendship with Touschek: "*He was my closest friend, the person I was closest to among the physicists who were in Italy, without any doubt [...] A bizarre character, perhaps a little crazy, but very cultured and extremely intelligent*" (L. Radicati, interview by L. Bonolis, Rome, June 6, 1997).

Fig. 2.10 *Physics with Intersecting Storage Rings*, 'Enrico Fermi Summer School' directed by Bruno Touschek, held in Varenna in 1969. *Credit* Italian Physical Society

2.16 1977–1978: At CERN in Geneva

Between 1977 and 1978, Touschek spent the last months of his life as visiting scientist at CERN, at a time when early plans for a giant electron-positron collider were being discussed. However, when LEP eventually came into operation in 1989, Touschek was no more there. He had prematurely passed away, on the 25th of May 1978, while he was participating in the planning of the proton-antiproton collider ($Sp\bar{p}S$) proposed by Carlo Rubbia, with whom in the late 1960s he had long discussions about the possibility of transforming a conventional accelerator into a proton-antiproton collider [22, pp. 59–60]: "*Clearly in his and in our mind at the time the proton-antiproton option was the logical continuation of the AdA–Adone line*."

According to Salvini, during a conference in Saclay in September 1966, a session was dedicated to Novosibirsk and the method of cooling antiprotons, as suggested by Budker [2, p. 62]: "[...] *Budker was only at the beginning of his report, and Bruno Touschek had understood everything; he was getting excited, could not keep himself [...] Bruno told us that morning: 'We cannot get highest energies with electrons, but we'll get them by proton-antiproton collisions. It is a most important development, and probably this is not the only way to tame antiproton beams*."

About ten years later, further recalled Rubbia [22, pp. 59–60],"*The fire of the proton-antiproton collision was still burning in the back of my mind, and I must say that so it was in the mind of Bruno […] As soon as he knew that the proton-antiproton collision adventure at last was actually going to start—although already terribly affected by his illness—Bruno decided to move immediately to CERN. I remember having long discussions with him first at CERN and then, toward the end, at the nearby Hospital de La Tour […]*".

At that time also Giorgio Salvini, who was taking part in the preparation of Rubbia's UA1 experiment, visited Touschek quite often to keep him informed [2, p. 65]: "*[…] almost every day [we] discussed the developments of UA1 in detail*."

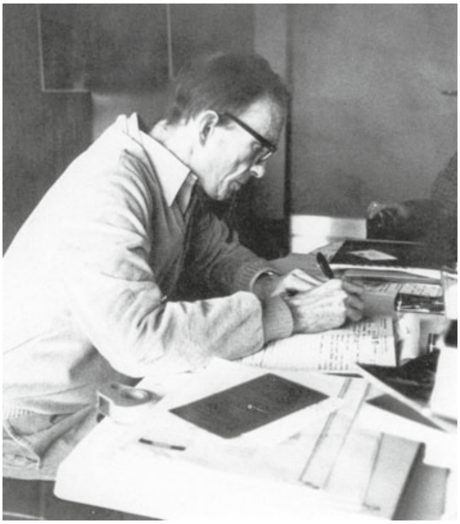

Fig. 2.11 Bruno Touschek during his last days, when he was visiting scientist at CERN. *Credit* Francis Touschek

Rubbia concluded his remembrance of Touschek by saying [22, p. 60]: "*I have learned from Bruno how to love matter-antimatter reactions. Without this fact, my own scientific career would certainly have been very different. So I believe it is the case for many of us.*"

Unfortunately Touschek did not live long enough to see his ideas triumph and to witness the discovery of the $W^{\pm}$ and Z^0 vector bosons and the related 1984 Nobel Prize in Physics to Rubbia and Simon van der Meer.

2.17 Conclusion

Bruno Touschek's small AdA (about 1.3 m in diameter, storing beams of 250 MeV) has opened the way to new bigger matter-antimatter colliders and precision measurements which have been instrumental in confirming our understanding of the basic building blocks of matter in the Universe and the fundamental forces that operate between them. The detection of the long-sought Higgs boson at the Large Hadron Collider at CERN in 2012, has eventually completed the Standard Theory of particle physics. The fundamental contribution of AdA as a progenitor of entire generations of colliders was recognized on 5 December 2013, when the world's first particle-antiparticle accelerator—still visible on the grounds of INFN Frascati National Laboratories—was declared an Historic Site by the European Physical Society. This important recognition has definitely marked AdA's role as a milestone in the Italian and European scientific heritage.

As historians, we are still left with the task of in-depth investigations related to the evolution of Touschek's theoretical thought during the twenty years or so between the war years—and his work on the betatron theory—to the late 1950s, when such a long process finally materialized into his daring and drastic proposal, that he considered "*the future goal*" of Frascati Laboratories: transform the electron synchrotron, that had just begun to function, into an electron-positron collider and explore the physics of matter-antimatter annihilations. His bold idea was wisely and enthusiastically converted into the decision to build a dedicated small prototype, AdA, the first ever matter-antimatter machine, which in the early 1960s set the stage for a new era in particle physics.

The period from Touschek's arrival in Italy at the end of 1952, to the end of the 1950s, during which he fully developed into a mature theoretical physicist dialoguing with prominent theoreticians of his time, has not yet been thoroughly studied. In particular his scientific production as well as his scientific correspondence with Heisenberg, which dates back to the early post-war period, and continued during the 1950s, has yet to be analyzed, as well as his letters with Wolfgang Pauli, himself born in Vienna from a prominent Jewish family, of whose work Touschek had always been an attentive follower since his early youth. They had an intense exchange of ideas during 1957–1958, at a time when much of Pauli's work was still centered on quantum field theory.[26] Such a dialogue with Pauli and with other theorists (notably Charles Enz, Gerhart Lüders, Markus Fierz, Kurt Symanzik, Luigi Radicati, Giacomo Morpurgo, Marcello Cini) was instrumental in the development of his ideas on QED and discrete symmetries, as well as in stimulating his own reflections on the CPT theorem, the solid conceptual base for AdA, as can be derived from correspondence of the period preserved within his papers at 'Edoardo Amaldi Archives' at the Physics Department of Sapienza University in Rome, and in published articles.

The analysis of Touschek's scientific life in the 1950s is thus to be pursued as one of the main keys to a deeper understanding of all the implications of his unique path towards what became a standard practice: using matter-antimatter annihilations to probe the ultimate nature of the basic building blocks of the Universe and their interactions.

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