My life in Physics

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A project on the history of science in Finland was launched recently, which calls for personal recollections by scientists that are or have been active in Finland [1–4], Fig. 1. I was appointed to the Chair of Elementary Particle Physics at the University of Helsinki in 1980, and have been granted an affiliation with the University as emeritus since 2013. Here I describe my scientific career and some of my research.

I write in English to make these recollections widely accessible. While my native language is Swedish I have studied, taught and worked in Finnish and English. My reminiscences may be inaccurate, and are subjective.

History of Science

The History of science in Finland aims at a comprehensive mapping of scientific life in the republic of Finland since 1918.

The History of science in Finland aims at a comprehensive mapping of scientific life in the republic of Finland since 1918. The project is jointly supported by the two national academies of science (The Finnish Academy of Science and Letters and The Finnish Society of Sciences and Letters).

Building on earlier histories of science in Finland, it broadens the field by incorporating new methodological tools offered by social studies of science, the history of knowledge and the global history of science and knowledge. It sheds light on the place of science and society, and vice versa, and poses new questions about the position and predicament of Finland in the world-system of science.

The project also makes extensive use of oral and written recollections by scientific practitioners in Finland. These testimonies will complement the archival and published sources that form the basis for the expected outcomes of the project: a multivolume book series (in Finnish, Swedish and English) as well as an on-line platform on the history of science in Finland.

The project is coordianted by the project manager **Stefan Nygård** (The Finnish Academy of Science and Letters & University of Helsinki) and the chief-editors of the book series **Heini Hakosalo** (University of Oulu), **Henrik Meinander** (University of Helsinki) and **Jari Ojala** (University of Jyväskylä).

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FIG. 1. Announcement of the History of science in Finland project. Web page of the The Finnish Academy of Science and Letters [1] on 7 March 2024.

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A. 1945 – 1973: Before my PhD

1. School years

I was born in 1945 and grew up in Grankulla (Kauniainen) near Helsinki. I attended grades 1-4 of folkskola (kansakoulu), followed by grades 1-5 in Grankulla samskola (both taught in Swedish). I finished the samskola with good grades, except in Finnish language which I found difficult. After the death of my father in 1961 we moved to Brändö (Kulosaari), which is a suburb of Helsinki. There I attended the gymnasium (lukio) of Brändö Svenska Samskola. I enjoyed the relaxed atmosphere of this school, which at the time was not highly ranked. I passed the nationwide studentexamen (ylioppilastutkinto) in 1964 with top grades.

My father was a diplom-ekonom (MBA) from the Hanken School of Economics in Helsinki and worked in business. My mother was from a well-to-do family but received no higher education, as was common for women at the time. She had no regular employment. Thanks to my father's business acumen we lived comfortably, and spent the summer months at a cabin on an island in Sibbo (Sipoo, east of Helsinki).

I had no close relatives or family friends working in science, but my father was fond of physical phenomena. Around the age of 12 I spotted the Scientific American magazine in a bookstore, and it greatly impressed me (later I subscribed to this journal for many years). I read books of popular science and enjoyed the courses on mathematics and physics at school, being lucky to have teachers that were motivated and supportive. Nevertheless, I had no clear notion of what to do after finishing the gymnasium, and did not conceive of physics as a profession.

In 1963 I visited, together with some of my classmates, the engineering physics (teknillinen fysiikka) department of the Helsinki University of Technology (HUT, now part of Aalto University). We admired the blue Cherenkov light emitted in the pool of the newly commissioned TRIGA nuclear reactor. We also saw fancy electronic gadgets, one of which could play Tic-tac-toe, and learned about research on computers. The newspapers wrote about the technical wonders being developed there by professors such as Erkki Laurila and Pekka Jauho.

2. University studies

I soon made up my mind to apply for studies at HUT after my graduation. This would allow me to learn physics while earning an engineering degree, which promised a solid profession. The numerus clausus was an added incentive: Together with studies in medicine, engineering physics (and architecture) at HUT was the most popular line of study for Finnish students at the time. Applicants were selected based on an intensive 4-week summer course, with weekly examinations. I would see how I fared in comparison with students from all of Finland.

I was accepted for studies in engineering physics, and started in the fall of 1964 at the new HUT campus in Otaniemi. I could begin my studies right after finishing school since my (hereditary) hemophilia disease made me unfit for the compulsory military service. The hemophilia has not affected my life significantly, in large part thanks to the excellent health care in Finland.

The basic math and physics education at HUT was efficient and focused on teaching calculational skills. I was less enthused by the compulsory courses in machine parts and technical drawing. The course in electronics during the second year was too application oriented for my taste. The studies anyway went well enough for the HUT Board to award me an encouragement prize as I finished the first part of the engineering degree in 1966. Thus reassured I decided to move to the University of Helsinki (UH), which had a line of study in theoretical physics. I had realized that I was more inclined to principles than practice.

Mobility between universities was less organized then than now. Anyway, my basic courses in math and physics at HUT were credited towards the MSc degree, so I lost no time. At UH, Pekka Tarjanne was a young and able professor of theoretical physics, who specialized in elementary particles. Professor Kalervo Laurikainen was building a research group in experimental high energy physics, based on an informal collaboration with CERN in Geneva and Dubna near Moscow (for a description in Finnish see the book [5]). I enjoyed the studies and got my MSc (filosofian kandidaatti) in 1968. This was a year of student upheavals also in Finland, but I mainly paid attention to my studies.

3. PhD studies at CERN and Oxford

The PhD studies were less structured than at present. There were some compulsory courses, but no time limits nor organised supervision. Financial support was provided by short-term teaching and research positions. When the holder of a higher level position went on a leave of absence (*e.g.*, for work abroad) the position was temporarily filled by someone of lower rank, with a chain reaction down to beginners such as myself. Support from funding agencies played a comparatively minor role. High energy physics was privileged in having an annual grant from the Academy of Finland, to facilitate the international collaboration. This funding was administered by the "Particle physics committee", composed of senior researches in the field. It allowed short and longer term travel, especially visits to CERN and Dubna.

The future seemed bright. I recall an admonition from professor Tarjanne, to the effect that anyone with ambitions for an academic career would have to do research abroad for some years. This obligation struck me as a privilege, as living abroad was one of my dreams. I was fortunate at this time to find a partner who shared my wish to experience the world. Forming a family while moving between short-term positions in various countries is challenging. This conundrum was resolved by my spouse, who took the risk of foregoing her personal career as an engineer. The reward for her was more time with the children and a rich cultural and linguistic experience, which opened a different career. I was privileged to learn physics at first rate centers, while enjoying a secure family life. During twelve years we moved between six countries, and each year to a new home.

The "two-body problem" is familiar to all couples with careers that require transferring between short-term positions at different locations. Finding suitable employment for both at the same place and time is difficult and may be impossible. In the past the solution was often that one spouse (usually the wife) followed the other, and searched for meaningful activities at each location. Mobility provides rich experiences, but the moves are stressful. Friendships hardly have time to form before they are broken (although some may endure). The frequent moves brought our family close together, as parents and children shared the experiences and family life provided continuity.

Already before my MSc degree professor Laurikainen offered me to join his group, and training in experimental physics at CERN. However, I was inclined towards theory and thus rejected his offer. In retrospect, this was the first of several times when I was rather obstinate to my superiors, following my own ideas of how to do physics. As it turned out, I was soon given an opportunity to join the CERN theory department in 1969 as a research fellow. I do not know how this came about, but it was a rather audacious project. CERN fellowships were attractive post-doctoral positions, with applicants selected by CERN. Finns were ineligible since Finland was not a member state. However, the collaboration agreement specified that Finland selects and supports its own visitors to CERN. Thus I became maybe the youngest, and certainly the least experienced, of fellows in the theory department[1]. Part of the financial support was provided by a grant from the Board (konsistori) of the university, flatteringly called "Helsinki University grant for exceptionally gifted young scientists". I held this grant until my PhD, during 1969 to 1973.

CERN had no program of PhD studies, and its staff was not expected to supervise students. I was not worried, but perhaps I should have been. Nothing was required and one was easily ignored in this large establishment. Fortunately I was introduced to senior physicists by other visitors from Finland. Keijo Kajantie, who later succeeded Tarjanne as UH Professor of Theoretical Physics, was particularly helpful. Thus I met Dr. Chan Hong-Mo, a CERN staff member who took me into his research group. Chan came to be my (informal) PhD supervisor, and provided crucial support. I once self-assuredly asked a senior CERN physicist to approve that some independent research of mine be published as a CERN preprint. That encounter did not go well, and might have become an obstacle to my career were it not for Chan's intervention. Clearly I was full of hubris, then as later. On the other hand, surviving in competitive environments requires self-confidence.

Curiously, my first publication was in a journal of medicine [6]. In 1966 I assisted a physician in a problem of mechanics, by calculating the optimal positions of tendon pulleys in surgery of the hand. This did not, however, presage a cross-disciplinary career. My predilection in research has been for logical deduction, inferring how experimental data may be described theoretically. I have focused rather (too?) narrowly on the physics of hadrons, to the detriment of other areas and related sciences. I do have a broad interest in science and humanities, but only at the layman level.

Around the time of my MSc degree Gabriele Veneziano published a paper [7] which immediately attracted wide attention. Hadron scattering amplitudes were known to have non-trivial properties, including "crossing symmetry" and "duality". Veneziano's discovery of an explicit analytic function which incorporated those features was the beginning of "dual theory". Research in this field continues even today in various forms, including string theory as an explanation of gravity. The emergence of the dual models, previously unknown in the field, allowed novices like me with some understanding of analytic functions to contribute. Thus my first physics paper [8] came about.

The stay at CERN in 1969 – 1971 provided a rocket start to my career in physics. Being immersed in forefront research I formed friendships with colleagues from all over the world. Together with Chan and others we applied the Veneziano amplitudes to data on hadron cross sections. This taught me much about experiments and the theory of hadron scattering, and strongly influenced my future research. On the other hand, I missed much of the basic graduate

[1] Formally I was a Visiting Scientist, but in practice I was treated as a fellow.

education that is required today, including courses on quantum field theory. This limited my possibilities to grasp and participate in theoretically advanced research. The Standard Model of particle physics was being formulated at that time, and string theory developed. Being phenomenologically minded I may not have contributed to those developments even if I had been better prepared.

In 1971 Chan was moving to the Rutherford Laboratory near Oxford in the UK, and suggested that I come along. The previously mentioned grant from the UH allowed me to visit the theoretical physics department of Oxford University in 1971 – 1973. My situation there was again a bit special. I did not have a PhD degree, but neither was I enrolled as a graduate student, nor associated with a college. In practice, I was associated with the postdocs and other long term visitors. I regularly visited the Rutherford Laboratory, continuing my collaboration with Chan and others, and enjoyed the advanced research environment in Oxford. Rudolf Peierls was the Professor and the department had many other famous staff and visitors. There were close connections to the research in experimental particle physics led by Professor Donald Perkins. While in Oxford I started to prepare for my PhD degree at the UH. To begin with I needed to get the fil.lic. (licentiate) degree, which was awarded in June 1972. It was becoming clear that taking care of such formalities were necessary for my academic career.

In spring and summer of 1973 I visited Helsinki, working at the Research Institute for Theoretical Physics. I defended my PhD thesis, which was a collection of my publications together with a summary. Since my native language was Swedish I took a university exam to document that I was fluent in Finnish. The language certificate allowed me to apply for positions which were otherwise restricted to Finnish speakers (foreign applicants could ask for an exemption from the President of Finland). My years abroad had begun to affect my skills in Finnish, so it was unwise to postpone the exam any longer. The Helsinki visit was timely also since it allowed our first child to be born in familiar surroundings. In September 1973 I began my first "real" postdoc, at the Institute for theoretical physics of the State University of New York (SUNY) at Stony Brook.

B. 1973 – 1981: Postdocs and Junior Faculty

1. Postdoc at SUNY in Stony Brook

Post-doctoral positions were offered for an initial term of one year, normally extendable to a second year. They were not tied to specific projects and tasks, as is common today. Postdocs were free to conduct research and collaborate according to their choice. My offer from Professor Chen Ning Yang (Nobel in 1957, at age 35) specified that:

> *In this position you will have no administrative or teaching duties,*
> *and you are free to pursue research work of your choice.*

On the other hand, the short duration of the position prompted quick results and publications. Postdocs typically applied for their next position about a year after starting in the previous one. Successful collaboration with senior colleagues would improve the possibilities to get positive letters of recommendation. It would also reassure prospective employers of one's usefulness. Two or three postdoc positions was considered "normal" in an academic career, then one was expected to find a position at the junior faculty level. That was a crucial and difficult transition.

The SUNY Institute for Theoretical Physics (now the C. N. Yang Institute, YITP) was a prestigious center created for and by C. N. Yang in 1965. It was closely associated with the SUNY Physics and Mathematics Departments. During my stay a series of discussions led by Yang and James Simons explored the relations between the gauge theories of physics and the fiber bundles of mathematics. Yang had created non-abelian gauge theory in 1954 and Simons was a renowned expert on geometry and topology[2]. I attended the seminars, although they were beyond my comprehension. Yang later described their outcome as:

> *It came as a great shock to both physicists and mathematicians in the 1970s that*
> *the mathematics of gauge theory, both abelian and non-abelian, turned out to be*
> *exactly the same as that of fiber-bundle theory.* [9]

The 1974 "November revolution" of particle physics occurred during my stay at Stony Brook. A heavy, long-lived particle was simultaneously discovered at the nearby Brookhaven National Laboratory (where it was called the "J") and at SLAC of Stanford University (which called it the "ψ"). The J/ψ was soon understood to be composed of

[2] Simons was at the time head of the SUNY math department. Later he created the Simons foundation which supports research in mathematics and fundamental sciences.

a pair of previously unknown, heavy "charm quarks". The binding energy of the charm quarks in the J/ψ is much smaller than the quark masses, giving the J/ψ features similar to ordinary atoms. A few years earlier (in 1969) experiments at SLAC had revealed that protons were composed of pointlike "partons", mostly light quarks and gluons. These discoveries showed that quarks were true particles, like electrons. Quarks and gluons are now described by the theory of Quantum Chromodynamics (QCD), a non-abelian gauge theory analogous to the (abelian) Quantum Electrodynamics (QED), which governs electrons and photons.

The main line of research in particle physics now turned towards properties of the heavy quarks and to "hard" scattering, characterized by large momentum transfers. These phenomena could be described using QCD methods similar to those of QED. I continued my studies of duality and soft hadron scattering, phenomena which differ qualitatively from those of atomic physics. Yang was a master of mathematical methods, but also interested in more phenomenological models. He suggested that I study a model of soft hadron scattering that he had previously developed. I was not interested, which was unwise and nearly cost me the expected second year extension of my postdoc. I was apparently rescued by Chris Quigg, who was then Assistant Professor and my close senior colleague at the Institute. Later I came to truly appreciate the genius of Yang, and I believe that he in turn forgave me. Yang was always very friendly and helpful.

2. Postdoc at Lawrence Berkeley Laboratory

In 1975 I moved to the Lawrence Berkeley National Laboratory (LBNL) for my second postdoc. LBNL is a federally funded laboratory with a broad science program. It takes pride in 15 Nobel Prizes in Physics and Chemistry since it was established in 1931 by Ernest Lawrence. The Laboratory is located in the hills overlooking the University of California Berkeley campus, with an incredible view over San Francisco Bay and the Golden Gate Bridge. The theory group had many famous physicists, including Geoffrey Chew and David Jackson. Chew was the main proponent of the S-matrix approach to hadron scattering, an area that I myself was working in. One of my more relevant results was obtained during this postdoc, but I did not directly collaborate with either Chew or Jackson. During my stay I occasionally visited the Stanford Linear Accelerator Laboratory (SLAC) on the opposite side of the Bay. There I met Stan Brodsky, with whom I was later to have a long-time collaboration.

I enjoyed physics and the possibilities to work abroad, together with my wife and our two children. Getting a faculty level position was quite uncertain, yet I was unwilling to adjust my research so as to optimize my career possibilities. Like many other scientists, I had not chosen research for the money nor for security. If and when there would be no more job offers there was Plan B. I would return to Finland, where I expected to obtain a short-term research position. This would allow time for finding a suitable job outside academia, *e.g.*, in computer programming. Society then seemed more supportive and understanding than at present. Now one might face a period of unemployment.

Already in 1972, before my PhD, I was informed that a tenured lecturer position in theoretical high energy physics was opening at the Niels Bohr Institute (NBI) in Copenhagen. I had previously visited there and enjoyed its informal atmosphere, as well as the liberal spirit of Copenhagen. In fact I carried a few Danish genes, as my great-grandfather emigrated from Jutland to Finland. This job opportunity came rather early in my career, but encouraged by my senior colleagues in Copenhagen I decided to apply. NBI was a prestigious institution and most of the 23 applicants were highly qualified. The position deservedly went to a more experienced physicist, albeit with a minority report of the selection committee favoring me.

In 1974 an Associate Professor position (apulaisprofessori) in theoretical physics became available at the University of Helsinki. I did not neglect this opportunity either, but the position again went to a more experienced applicant. In 1979 I was encouraged to apply for a position at DESY, the German accelerator laboratory in Hamburg (Leitende Wissenschaftler auf dem Gebiet der Theoretischen Physik). I do not know the other applicants nor how I fared, but I was not selected.

3. Senior stipendiate at Nordita

The Nordic Institute for Theoretical Physics (Nordita) was located on the premises of NBI in Copenhagen, being funded by the Nordic Council of Ministers. It had several tenured professor positions, 3+3 year assistant professors and a stipendiate (postdoc) program reserved for Nordic citizens. The possibility of offering me a "senior stipendiate" position, roughly equivalent to an assistant professorship, was raised by Nordita Professor G. E. Brown in a letter to Kajantie in 1974. He had presumably discussed this with Professor Aage Bohr, who was then Nordita Director. Nordita was closely linked to the NBI, reflecting the establishment of Nordita in 1957 at the initiative of Niels Bohr.

The local administration was handled with little bureaucracy. Decisions concerning appointments lay with the Board, which was composed of senior Nordic physicists appointed by the governments of the Nordic countries.

I happily accepted the offer of a senior stipendiate position at Nordita in January 1977. There was some initial confusion. I had been informed that this would be a three year position, but the actual offer was for two years. I was told that this was a formality, an extension for a third year was practically ensured. My situation was shared by Fred Myhrer, who received a senior stipendiate offer around the same time. We were apparently the first senior stipendiates at Nordita, and the conditions for this type of position had not yet been fully defined. Both of us argued that our rights and duties should be equivalent to those of the assistant professors, and this was in the end agreed to. In September 1977 I began a successful and enjoyable four-year stay at Nordita.

The institute achieved a critical size in its several subfields of theoretical physics through integration with the research community of NBI. My office was located in the F-building with the NBI particle physicists, at the far end of the Blegdamsvej premises as viewed from the Nordita administration in building B. I had close and daily interactions with the High Energy Physics faculty and postdocs of Nordita and NBI. The NBI/Nordita HEP group jointly planned the research activities, including seminars and workshops, the hiring of postdocs, etc. I also enjoyed interactions with the experimental HEP group led by Knud Hansen. With Knud we organized two memorable workshops on jet physics [10, 11], at the time when quark jets were being discovered.

There was an active social program on Blegdamsvej, organized by the informal "Kommutator" society. Potluck dinners and excursions regularly brought together also the spouses and children of the physicists at NBI and Nordita. The Kommutator seemed like an "afterglow" of the fabulous Niels Bohr era – its activities sadly decreased with the retirements of the Old Guard.

When I arrived in Copenhagen my research into duality and phenomenological models of hadrons were nearing an impasse. Some deeper insights seemed to be required for progress. Perhaps this situation made me (who is often rather obstinate) receptive when Professor Aage Bohr suggested that I turn my studies to Quantum Chromo Dynamics (QCD). This quantum field theory was known to govern the strong interactions of quarks and gluons, and thus also of hadrons and nuclei. Even though found to be a consistent and correct theory, it was challenging to explain experimental results using QCD. This was particularly the case for the soft interactions that I had been working on. Towards the end of my stay in Copenhagen I got an intuitive feeling for a QCD approach to hadrons that I have been developing to this day, with steady (if slow) progress. I return to this below.

Nordita started an exchange program with the DESY laboratory in Hamburg, which had a significant impact on my career. Aage Bohr took the initiative on behalf of Nordita, while Tom Walsh was our contact person and theory group leader at DESY. During 1978-79 Tom made several visits to Nordita, while Per Osland and I made corresponding visits to DESY, each lasting a couple of weeks. The collaboration was motivated by the start-up of the PETRA electron-positron collider at DESY. Osland, Sander, Walsh, Zerwas and I developed a QCD model for gluon jet production at PETRA. Sander provided the decisive contribution by casting the model into a "Monte Carlo" simulation program, the first of its kind in particle physics. The discovery of gluons turned out to be the principal contribution of PETRA, and our program was extensively used. The five alphabetically ordered author names were often abbreviated to the first one, so the program became known as the "Hoyer model". Although undeserved, this helped me gain a chair at the University of Helsinki.

C. 1978 – 1980: Appointment as Professor at the University of Helsinki

Professor K. V. Laurikainen had been the driving force in establishing research in elementary particle physics and in strengthening theoretical physics at UH. His retirement in 1978 was a major event. The University decided to open two positions, one as full professor in elementary particle physics and the other as associate professor (tenured) in high energy physics. The full professor would serve also as Head of the Department of High Energy Physics, which included responsibility for the experimental collaboration with CERN and Dubna. The positions were not further specified and thus open to physicists in both experimental and theoretical particle physics. The research of theorists is more easily recognized than that of experimentalists, who work in big collaborations.

There had been a strong expansion of physics in Finland during the previous two decades. Consequently most professors were far from retirement. As the era of new positions was coming to an end it seemed likely that the two openings in particle physics would be the last ones for the next decade or so. This indeed turned out to be the case.

University positions in Finland were at the time generally held by Finnish citizens. Professorships were advertised in local newspapers and the language requirements discouraged foreign applicants. Conversely, Finnish scientists rarely moved to tenured positions abroad. It was thus important that the few available professorships were filled as objectively and openly as possible. The external experts were asked to evaluate the applicants solely based on their scientific merits for the position as announced. They were not to consult with the department or even discuss among themselves. The professors of the faculty could influence the selection of experts, but the expert opinions then carried great weight in filling the position. The applicants received a copy of the evaluations and could complain to the University Chancellor if they felt that the recommendation made by the faculty was unfair.

There were 11 applicants for the full and 10 for the associate professorship, two of whom were experimentalists. The applicants were to send five copies of each of their publications to the university. These were distributed to the experts, who were asked to form their opinion based only on this material. The faculty chose five well-known foreign physicists, of which one was an experimentalist, to evaluate the applicants for both positions.

All applicants were Finns except Masud Chaichian, whose application was something of a surprise. Chaichian was from Iran and then working as a postdoc in Helsinki. It turned out that he got the best evaluations for both positions. Although Chaichian lacked the formal language qualification, he had demonstrated his ability to teach in Finnish. I was the runner-up, closely followed by Hannu I. Miettinen. The faculty decided that the full professor, who had administrative duties as head of department, needed to have the formal language qualification. I was therefore proposed for this position, and appointed by the President of Finland (Kekkonen) on 28.11. 1980. Chaichian became associate professor, and was promoted to full professor in 1992.

The result of the application and selection process was unpredictable, although theorists had an advantage due to their better visibility. The expert evaluations were decisive but not unanimous, and needed to be averaged in some way. The final ordering of the candidates had an element of chance, and strongly influenced the further developments of particle physics in Finland. My good friend Hannu Miettinen, who narrowly missed being selected, was a dynamic physicist with strong outreach capabilities. He went on to organise a very popular physics exhibition in Helsinki in 1982, and was instrumental in creating the science center "Heureka" a few years later. He would undoubtedly have made a strong impact as professor.

I have described the above procedures in some detail to illustrate the contrast with the present situation. Nowadays the applicants are evaluated using several criteria, including leadership experience. The ability to secure funding (especially from the European Research Council) has become increasingly important since research at universities is funded by external sources. Teaching capabilities carry more weight, and the needs of the department are taken into account. The process is more subjective and less open than previously. On the other hand, researchers are more mobile and can thus apply for a larger number of positions.

D. 1981 – 1994: Professor at the University of Helsinki

My predecessor K. V. Laurikainen was appointed in 1960 to the then newly established Chair of Nuclear Physics. At the same time the university created the department of Nuclear Physics with Laurikainen as Head. He started by organizing the research and teaching of theoretical physics, which became its own line of study, in parallel to physics. Laurikainen then considered various options for experimental research before settling for a collaboration with CERN and Dubna. These developments are covered in the book [5] by Jorma Tuominemi.

By the time of my appointment in 1980 the department, now renamed Department of High Energy Physics (SEFL), disposed of considerable resources. In addition to the two professor positions previously discussed, Matts Roos had a personal chair won in a university wide competition. There were a number of assistant positions, laboratory personnel and two secretaries. SEFL was located in a building of its own (built at the initiative of Laurikainen) together with the Department of theoretical physics, the Research Institute for theoretical physics and a Computing center for physics. Laurikainen had been a primary mover in the establishment of all these institutions. Lobbying for these resources and securing their administrative independence from the main physics department generated strained personal relations.

According to the University statutes the administration was led by the full professors. They formed the Faculty council, where joint issues related to resources, appointments, degrees, *etc.* were decided. Being the only full professor at SEFL I was department chair, and also responsible for matters related to the building (including the janitors). Even persons with more experience and leadership training would have found it challenging to follow in Laurikainen's footsteps. My performance is best judged by others, but let me note a couple of subjective observations. I have always preferred relations at an equal level, *i.e.*, not enjoyed ordering others nor liked to be told what to do. My passion is for science, whereas administration and ranks are of secondary interest to me. I have come to understand that this attitude is not shared by all.

Experimental high energy physics in Finland was pursued only at SEFL, yet all its three professors were theorists. Initially the researchers analysed bubble chamber pictures from experiments at CERN and Dubna. In 1979 a group of SEFL physicists led by Dr. Jorma Tuominiemi joined the UA1 Collaboration at the CERN proton-antiproton collider. The UA1 detector registered particle tracks electronically, almost with bubble chamber accuracy. The Finnish group contributed significantly due to their expertise in event reconstruction. UA1 soon gathered fame by discovering the heavy vector bosons $W^{\pm}$ and Z^0 in 1982-83. In 1984 another group of SEFL physicists led by Dr. Risto Orava joined the DELPHI Collaboration, which was preparing for experiments at the e^+e^- collider LEP at CERN. This time SEFL also contributed with industrially produced hardware, developed in the newly established detector laboratory. See [5] for more details.

The experimental efforts of SEFL were planned and realized by the physicists involved. It was not fair that they had to do this from junior positions, especially as Tuominiemi had been group leader from the start of the research activities in 1965.

The increasing scope of Finnish involvement in CERN experiments raised the issue of CERN membership. Denmark, Norway and Sweden were founding members of CERN in 1954. At that time Finland could not, for political reasons, join a West European nuclear research institute. Even at the start of the bubble chamber activities in the 1960's the collaboration with CERN and Dubna had to be balanced. By the 1980's the political constraints had diminished, and Finland had political ambitions to align more closely with Europe. However, the financial aspect remained daunting. The annual CERN member fee was around 40 million Finnish marks (FIM), which was more than 70% of the total funding for natural sciences by the Finnish research council (the Academy of Finland). In addition, an annual budget of some 15 MFIM was estimated to be needed for domestic research expenditures. This was far more than the funding for Finnish high energy physics research at the time, which was around 2.3 MFIM.

Scientists in other fields were understandably worried that their funding would be cut if Finland joined CERN. Particle physicists argued that CERN membership would open possibilities for joining other European research organizations such as ESA and ESO (which actually happened). There would be a tidal change in Finnish research funding. CERN provided opportunities for training young scientists in an international environment, and for developing advanced technology at an industrial scale.

The Finnish government decided to open negotiations with CERN in August 1989, aiming at full membership. The decision may have been influenced by the rapidly changing political situation in Europe, symbolized by the fall of the Berlin wall. Finland aspired to join the European Union and was fairly wealthy, hence could no longer abstain from contributing to joint projects. I participated in the negotiations, including the CERN Council session where Finland was officially invited. Soon afterwards there were events which had a big impact on my duties.

I had an opportunity for a sabbatical year in 1990-91, and was invited by my colleague and collaborator Stan Brodsky to spend it at SLAC (the Stanford Linear Accelerator Center). This was very attractive to me scientifically. On the other hand, visiting CERN would have been natural from the point of view of my administrative responsibilities. My year at SLAC indeed turned out to be exceptionally fruitful for my research.

During my absence circumstances were changing at the University of Helsinki. A new law concerning the University was passed by parliament in February 1991, restructuring its administration. Members of faculty councils as well as department chairs were henceforth to be elected by the staff and students. As Finland was becoming a member state of CERN the organization of experimental high energy physics needed to be refurbished. It was decided to establish a Research Institute for High Energy Physics (SEFT), which was administered by the University Board. The SEFL laboratory personnel was moved to SEFT, and SEFL became a part of the main physics department.

These developments implied changes in my responsibilities after the sabbatical year. I was nevertheless surprised at being freed of all administrative duties. From then on I served on no body related to the University or to CERN. My teaching and research continued as before, and I had normal, friendly relations with my colleagues at the department. In these somewhat awkward circumstances the offer from Nordita came as a welcome surprise.

E. 1994 – 2002: Director of Nordita

1. *Activities in Copenhagen*

As previously mentioned I was in 1977–81 a senior stipendiate at Nordita, the Nordic Institute for Theoretical Physics. During this time I took an interest also in organisational matters, at the level expected for a junior faculty. I valued that Nordita and NBI (the Niels Bohr Institute) formed a virtually seamless scientific community, with complementary responsibilities. NBI was the physics department of Copenhagen University, while Nordita catered to theoretical physics in the Nordic countries.

Nordita was established in 1957, in a process that paralleled that of CERN (for a history and presentation of the institute see [12, 13]). It was run on something of an *ad hoc* basis until Nordic cooperation was formalised with the establishment of the Nordic Council of Ministers (NCM) in 1971. Being administered by a political body was both a boon and a bane. Nordita received stable financial support with little interference in its daily activities, hence minimal bureaucracy. Over the years politically motivated demands of "Nordic usefulness" increased, however. NBI and Nordita professors used to serve as Nordita Directors, whereas the NCM followed a strict rotation of civil servants between the Nordic countries. There were pressures to hire a Director from another Nordic country when I received the offer in 1994.

The position as Nordita Director was very appealing to me. Copenhagen offered an international environment of advamced research in physics. Nordita could largely organise its own administration, everyday matters being handled by an experienced secretariat. Professors of physics at Nordic universities served as Board members, with firsthand understanding of the needs and interests of the institute. The Nordita professors and assistant professors were eminent scientists, dedicated to research and training. They had a central role in the planning and execution of all activities. A guiding principle was to develop and apply common methods of theoretical physics to nuclear and particle physics, condensed matter and astrophysics. The flexibility of Nordita allowed to quickly share new developments with physicists at Nordic universities.

The Nordic countries have a long history of interactions (including the occasional wars), dating back at least to the era of the Vikings. This forged similar values, culture and modes of government. There is much cross-border business and trade, more recently also military cooperation. Yet joint scientific institutions are rare – Nordita is one of the few significant exceptions. Science is universal and there is global competition for the best researchers. The Nordic countries are situated at the fringes of central Europe with altogether about 27 million inhabitants, corresponding to a medium sized European country. Each country on its own has limited human and infrastructure resources. Nordic cooperation in science makes eminent sense but is hard to establish. It took World War II and the world-leading Copenhagen center for physics to create Nordita in the 1950's – and even then it was a difficult undertaking.

Nordita's international standing allowed to attract first-rate physicists to its positions, for visits and to the conference program. Activities could be arranged at short notice, both in Copenhagen and elsewhere in the Nordic and Baltic region. The practical arrangements were supported by the secretariat headed by Helle Kiilerich. Young Nordic and Baltic physicists were trained in several ways. There were "Master Class" weeks for advanced undergraduate students, "Summer schools" for PhD students and postdocs, and a fellowship (1+1 year) program for postdocs. Over the years these activities created a network of scientific contacts in the region.

The Nordic usefulness of Nordita was further enhanced through special initiatives. The relevance of physics methods in areas such as climate, medicine, ecology and finance, and the communication of this to students, science administrators, to teachers at different levels and to the general public was discussed in 1999 at the "Methods Meet". My letter of invitation began with:

> *Human activities are increasingly influencing local and global environments. Our societies are facing difficult choices in regulating activities which affect, e.g., climate (global warming), natural resources (energy use, fishing quotas) and pollution levels. The structure of social interactions (in communications and finance, for example) are likewise growing more complex.*
>
> *Optimal responses to such challenges should be guided by evaluations of competent scientists. Physicists are trained to understand interrelations between complex phenomena, and they increasingly apply their skills in multidisciplinary research of direct relevance to society.*
>
> *Nordita, the Nordic Institute for Theoretical Physics located next to the Niels Bohr Institute in Copenhagen, wishes to promote the discussion of these issues in the Nordic area. I would therefore like to invite you (or your representative) to the workshop 'Methods Meet: Physics and Topical Issues of Society' that will be held at Nordita on 4-5 November 1999.*

In September 2001 Nordita arranged the school "Physics of Climate". The report to NorFA, the Nordic funding agency, began with:

> *Physics skills are useful in many areas outside physics. In particular, there is a steady flow of physicists to areas like climate, which are of high importance for society and pose challenging research problems. Physicists with the confidence and perspective to change fields have made important contributions in their new environments.*
>
> *There is a need to make such opportunities better known among physics students. Conversely, many established researchers in applied areas wish to get into contact with good physics students and possibly hire them into their research groups. Summer schools where researchers from other fields lecture to physics students offer a possibility to exchange information.*
>
> *"The physics of climate" school attracted internationally well-known climatologists as lecturers, who clearly appreciated this opportunity of meeting and discussing with physics students. There was also a strong interest among students to attend the school, of whom many had no previous experience in climate.*

A discussion arranged by Nordita with physics representatives of the Nordic research councils confirmed that the funding principles and procedures of all the councils were similar. However, each one had its own schedules and there was little, if any, coordination in the selection of experts. Efficiency might be increased by a joint evaluation of the applications submitted to the councils. The larger pool of proposals would allow to better compare the projects in each subfield, and thus identify the best projects within the Nordic area. If each council funded its own, jointly selected proposals no transfer of resources between the countries would be needed.

2. Nordita moves to Stockholm

My term as Nordita Director in 1994 – 1998 was extended to 1998 – 2002. Towards the end of my second term ominous signs were in the air. Nordic cooperation was generally felt to have stagnated and political priorities shifted to European collaboration and the EU. This led the Nordic Council of Ministers (NCM) to initiate studies on how to renew its activities. The proposals, although well argued and motivated, failed to arouse much enthusiasm. The NCM began to reconsider its mission and budget, of which a large fraction supported the Nordic institutes.

Within a year after I left Nordita the NCM decided to hand over all its institutes to national host organisations, and to cease their financial support in the course of a few years. For Nordita the natural host was the University of Copenhagen. To the consternation of many the University declined the offer. In this situation my successor, Professor Petter Minnhagen of Umeå University, made a call to other Nordic institutes for taking over the administration of Nordita. The KTH Royal Institute of Technology together with the Universities of Stockholm and Uppsala declared their interest. This came as a surprise to the Danish authorities, who had apparently planned to take over Nordita in their own way. Tensions rose also between the Director and the Faculty of Nordita. Finally I was asked to return as Director for 2005-06. This was against the NCM regulations, which imposed a strict time limit of eight years on Nordic employment. The rules were reinterpreted to accommodate the situation.

The Nordic ministries of research meanwhile debated the renewed Danish interest in Nordita, with virulent exchanges between the Danish and Swedish authorities. However, the die had been cast. Nordita was moved to Stockholm and my task was to oversee the consequences on behalf of Nordita. The tenured scientific staff was offered the possibility of relocating to Stockholm or staying in a Copenhagen "branch office" hosted by the Niels Bohr Institute. The Nordita secretariat was dissolved, but Helle Kiilerich was asked to provide administrative support for the activities remaining in Copenhagen.

The move was stressful, and implied some loss of the international Nordita "brand name". The Niels Bohr International Academy was soon established as a successor to Nordita in Copenhagen. In Stockholm Nordita has been well integrated into the AlbaNova University Centre, and received considerable project support from Swedish foundations. The plan was that the national research councils of the Nordic countries would participate in the financial support of Nordita, together with the host universities. This has turned out to be difficult to realize. The NCM continued its support at a reduced level for many years, but recently decided to stop. In the absence of other Nordic funding it appears that Nordita can be funded only from Swedish resources. It remains to be seen how this affects the Nordic role of Nordita.

Much could be gained by increasing scientific collaboration between the Nordic countries. This requires political will at government level. As European integration proceeds and mobility increases the benefits of a regional pooling of resources should become obvious. Nordita (together with a handful of other institutes) has provided an example, and will hopefully be able to continue supporting Nordic integration in theoretical physics.

F. Physics related activities

1. Summer schools and courses

My success as a university teacher was less than overwhelming. Students who came to ask for a project assignment often failed to return. I suspect that I scared them away, by discussing unresolved issues that I found fascinating, whereas what they wished was a simple and well-defined task. Altogether I supervised only three PhD theses. Those three students were truly smart, apparently not easily scared, and their theses contributed significantly to topical research.

My regular university lectures probably appealed mostly to the gifted students. I found it hard to resist my interest in physical phenomena, paying insufficient attention to the students who struggled with the basics. I liked to teach more advanced courses, and the department apparently agreed that this was for the best.

I thoroughly enjoyed interacting with students at summer schools and courses. Already during my first stay at Nordita in 1977-81 and many times later I co-organized such 1-2 week events in particle physics. There would be a handful of lecturers and at most 50 PhD students from the Nordic and Baltic countries or further away. The schools were usually held at a remote location, to encourage interactions also outside the regular lectures. They provided opportunities to discuss methods and phenomena in a relaxed atmosphere. The discussion sessions, often arranged each day after the lectures, were especially enjoyable. Any topics related to the lectures and beyond could be raised, and the lecturers would try to answer as best they could. There was no specific curriculum to be mastered, so one could experience the pure joy of science.

The "International Graduate School" program of the German Research Council (DFG) had a similar format, with a series of events scheduled over several years. I joined in such a collaboration between Giessen (Ulrich Mosel) and Copenhagen (Knud Hansen), which was extended to Helsinki when I moved there in 1981. The students and lecturers of these schools came primarily from the participating universities.

2. Physical societies: FPS and EPS

I am a member of the Finnish Physical Society (FPS) and of the Physical Society in Finland (a smaller society, mainly with Swedish-speaking members). I served on the Board of the FPS in 1989-95, the last two years as chair, and was appointed Fellow in 2016. The FPS comprises a large fraction of all Finnish physicists working at universities, in industry and at gymnasiums. It organizes the annual "Physics Days" at alternate locations in Finland, which covers topics in all subfields of physics and is well attended. The Days bring physicists together and counteract the trend of increasing specialization.

A few years before I joined the FPS Board there was a heated debate concerning the traditional society journal *Arkhimedes*. The chair (Hannu Miettinen) felt that Arkhimedes was unsuitable for distributing news about physics and the society, and wanted to change its contents and format. This raised strong opposition, and led to the creation of a second society journal, *Fysiikka Tänään* ("Physics Today"). This had shorter articles including photos, and centered on current developments. A compromise was reached several years later. Arkhimedes was modernized and the publication of Fysiikka Tänään (1987-96) terminated.

Another controversy occurred in 1989, when the FPS issued a recommendation for Finland not to join CERN. This was not liked by the particle physicists, who at the time were not represented on the FPS Board. It illustrates the difficulty of taking a position on issues related to subfields of physics. Since then the going has been smoother, but also less engagement in society affairs. Yet the society continues to have important tasks. In connection with its recent 70 year anniversary a number of profiles and interviews with past and present Finnish physicists were published. These are available on the FPS home page and are of lasting historical value.

I was a member of the Executive Committee of the European Physical Society (EPS) in 2003-06. The EPS was established in 1968 as a society for all European physicists. It has individual members and serves also as an umbrella organization for the national physical societies in Europe. Coordinating physics in Europe is challenging, as research and education is organized differently in the various countries. The UK and German societies together account for 2/3 of all physical society members in Europe, each having an order of magnitude more members than, *e.g.*, the French Physical Society. The EPS publishes the member journal *Europhysics News*. The national society journals are generally available only to their own members.

A central task of the EPS is to bring the interests and views of physicists to the attention of policy makers, especially in the EU Commission. The EPS actively supported and engaged the physical societies of eastern Europe when they were freed from the Soviet Union in the 1990's. At the global scale, EPS promotes physics for development and is liaising with other regional physical societies. It had an important role in organizing events such as the *The World Year of Physics* (2005) and the *International Year of Light* (2015).

Getting to know physics related activities in other European countries was interesting and rewarding for me. However, I noted after a while that I was out of my depth. The main responsibilities of the Executive Committee are in science policy and coordination. I can theorize about such matters, but accomplishing them is not my forte. In this sense my EPS experience was sobering.

3. *Scientific academies*

Finland has two academies of science (and two covering technology), mainly for historical reasons. The Finnish Society of Sciences and Letters was founded in 1838, when the Swedish language had a central role in politics and culture. Now the society is bilingual in Swedish and Finnish. The Finnish Academy of Science and Letters was established in 1908, catering especially to Finnish-speaking scientists. Today the academies collaborate and invite new members largely independently of mother tongue and citizenship. I have been honored by membership in both.

In keeping with tradition, the academies organize scientific presentations, mainly by and for their own members, but open to the public and held at a popular level. The academies strive to increase the general appreciation and understanding of science. In Finland as elsewhere, the academies offer their members' broad expertise as supprt to policy decisions. Being private institutions without significant state support they can provide objective advice.

I have very much enjoyed the possibilities to meet and discuss with my fellow academy members, most of whom work in other branches of science and humanities. They have much experience and many engagements in society, providing valuable insights.

4. *The ELFE Project*

In 1994 the Nuclear Physics European Collaboration Committee (NuPECC) endorsed a proposal for a "European Laboratory for Europe" (ELFE). The project involved constructing a continuous electron beam with energy in the 15 . . . 30 GeV range, for studying the structure of protons and nuclei. The electron energy was high enough to resolve the quark and gluon constituents of matter, whose interactions are governed by Quantum Chromodynamics (QCD). This was an area central to my interests, and so I was invited to join the Initiative Group for ELFE in 1995.

The initial plans did not specify where such a facility should be constructed. An option that soon emerged was to use the HERA collider at DESY in Hamburg as a "stretcher ring", to achieve a continuous beam. Preliminary plans for the accelerator and detectors were presented to the DESY management at a meeting in February 1996, where I summarized the physics opportunities [14]. This stirred interest at the other big German laboratory GSI near Darmstadt. They proposed a solution based on an electron-nucleon/nucleus collider with energy up to 5+50 GeV. The relative merits of the two proposals were compared at a meeting held in Seeheim (near Frankfurt) in March 1997, where I again covered the physics opportunities. Later a third option for ELFE was considered at CERN.

I also participated in other ELFE-related activities, such as the EU networks "HaPHEEP" (1997-2000) and "ESOP" (2000-2003). They involved the training of PhD students and postdocs through joint research projects and meetings. There was a series of biannual conferences on the "Electromagnetic Interactions of Nucleons and Nuclei" (EINN), funded by the European Science Foundation and held on the Greek island of Santorini. When it was my turn to chair the EINN conference in 2005 it was decided to explore alternative venues. Thus I got the welcome task of making a tour of the Aegean islands, visiting hotels with conference facilities. The island of Milos was finally chosen for this and the following conferences. European hadron physics was furthermore promoted through the EU I3 projects "HadronPhysics", to which I contributed as a member of the Steering Committee (2007-2009). All these activities were valuable and enjoyable to me.

In the end the ELFE project did not materialize. DESY opted for the "TeV-Energy Superconducting Linear Accelerator" (TESLA) project, colliding electrons and positrons at very high energies in conjunction with an X-ray free electron laser (XFEL). Only the XFEL was finally approved and constructed. GSI went ahead with the "Facility for Antiproton and Ion Research" (FAIR), which is currently under construction. Hadron physics similar to what was planned for ELFE will be studied in the PANDA experiment at FAIR, using antiprotons with energies up to 15 GeV. I was chair of the PANDA Theory Advisory Group during 2009-2013. CERN did not seriously consider the ELFE proposal in its future planning.

"ELFE physics" is presently studied mainly in the US, at the Jefferson Lab in Newport News, VA. The Jlab continuous, high intensity electron beam was raised from an initial 4 GeV to the present 12 GeV, with plans for a further upgrade to 22 GeV. A higher energy (10+275 GeV) electron-ion collider (EIC) is approved to be built in the coming decade at the Brookhaven National Laboratory on Long Island, NY.

ECT*

The European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*) was established in 1993 at the initiative of European nuclear physicists. It is located in Trento (Italy), at the southern foothills of the Alps, in a magnificent ducal villa from the early 17th century. The infrastructure and financial support of the Autonomous Province of Trento has been essential throughout the 30 year existence of the ECT*. Additional support is obtained from national and EU sources. ECT* arranges workshops on a wide range of topics, trains graduate students and hosts an in-house research program with staff and postdocs.

The ECT* Board and Director determine the scientific activities of the institute, based on proposals made by physicists associated with the centre. In 2004 I was invited to join the Board, and served as Chair in 2006-08. This was an interesting and rewarding task. My fellow Board members and the Director, as well as the scientific secretary, Professor Renzo Leonardi, became close colleagues. I got a broad view of topical physics research and of European science policy. Among physicists it was usually straightforward to reach agreement on the relevant issues.

In 2007, while I was chair, the Province of Trento terminated the "Istituto Trentino di Cultura", which administered ECT*. To safeguard the continuation of its local support ECT* needed to be incorporated in the new provincial research framework. The institute was welcomed as a center of the Fondazione Bruno Kessler, a large, multi-faceted research organization then created by the Province. The "European" nature of ECT* had from the beginning been established through the European Science Foundation (ESF) in Strasbourg: ECT* is an institutional member of the ESF Associated Nuclear Physics European Collaboration Committee (NuPECC). The national research councils of Europe left the ESF in 2014, forming Science Europe to coordinate their activities in Brussels. ECT* is now registered as a European Research Infrastructure of the EU, and maintains its membership of NuPECC.

ECT* was fortunate to have Jean-Paul Blaizot (Saclay) as Director during 2004-08, coinciding with my time on the Board. Towards the end of my term the Board had to identify the next Director. There were many constraints. The Director had to be an excellent physicist with broad international contacts. Good administrative and diplomatic skills were required, in interactions with the local institutions and with the European science community. ECT* could cover only the additional costs of living in Trento. A major part of the salary would need to be paid by national sources, or be based on retirement income. There were no precise restrictions on nationality, but some rotation was desirable.

Fortunately there was an excellent and interested candidate, Professor Achim Richter (Darmstadt Technical University). He had all the qualifications and moreover scientific contacts with physicists at the University of Trento. There were also other possibilities, and quite some maneuvering. In the end Richter was chosen and served ECT* very well.

According to the ECT* statutes an external review is held every five years. I experienced the 2007 review, when the committee was chaired by Francesco Iachello (Yale). The review concerned all aspects of the ECT* activities and judged how well they lived up to the aims of the institute. The committee interviewed the Board and the Director as well as the scientific staff, postdocs and secretaries. In 2013 I was asked to chair the next review, and we conducted a similar exercise. Most of the review committee members had previous experience with ECT* and were thus in a position to discern both the pros and the cons of the activities. The evaluations were conducted in a positive spirit, with the intention to provide useful feedback. They were quite helpful for the institute and its financial supporters.

CP3

While at Nordita I was fortunate to hire Francesco Sannino as a postdoc in 2000, using EU network funding. He had a double PhD degree from Naples (Italy) and Syracuse (USA) and came to Nordita from a postdoc at Yale University. Francesco is one of the most dynamic physicists I have known. By 2009 he was Professor at the University of Southern Denmark (SDU) in Odense and creator/Director of the CP3-Origins Centre there. Francesco had won a big grant from "Danmarks Grundforskningsfond", which funds Centers of Excellence for periods of 5+5 years. Although Francesco carried the full responsibility for CP3 he wished to have an advisory Board, and asked me to chair it. I stayed on until 2016 – it was a fascinating experience.

Francesco invigorated particle physics at SDU, creating a third Danish center on a par to those in Copenhagen and Aarhus. Francesco's scientific expertise and social skills quickly attracted talented physicists and eager young students to CP3. He took excellent care of everyone, supporting grant applications and making students feel welcome and relevant. He secured many faculty positions at SDU, both at the physics and mathematics departments. The university gained by hiring highly qualified scientists who had been attracted to Odense by CP3. This fulfilled the aims also of the research council, which wanted a lasting impact for their investment. The CP3 outreach to schools and the general public was admirable. My role was limited to being a sounding board, but it was rewarding to observe how much can be achieved with the right skills, attitudes and circumstances.

G. Research

My approach to physics has been shaped by the circumstances, as well as by my (dis)abilities and inclinations. A listing of my publications may be found in the Spires data base [15] [3]. I start with some general remarks, and then briefly discuss the topic of bound states which I have been working on (and off) for more than 40 years.

1. Generalities

Particle physics focuses on the the basic constituents of matter, trying to establish their properties and interactions. A handful of such constituents are known today: The quarks and leptons, the vector bosons and the Higgs particle. They form the "Standard Model" (SM), a relativistic quantum field theory with a local "gauge" symmetry. The SM was constructed based on the data available in the early 1970's and has since passed a multitude of increasingly stringent experimental tests.

Particle physicists specialize within a wide range of methods, from hardware (experimental apparatus) through data analysis and phenomenological descriptions to mathematical physics. I am somewhere in the middle of that range. I follow the experimental methods and results, and try to describe the data in terms of the SM, especially within the strong interactions (Quantum Chromodynamics, QCD). I enjoy considering all kinds of physical phenomena.

Like other human endeavors, physics is a social undertaking, influenced and inspired by mutual communication, collaboration and competition. Success is measured by experimental discoveries and convincing explanations. Marketing is required to make one's achievements widely known and appreciated (I find this difficult). The rewards are in the form of citations, prizes, positions and funding.

Theoretical physicists mostly collaborate in small groups, or work individually. I have especially enjoyed and profited from collaborations with Stanley Brodsky (Stanford). We share a strong feeling for physics and our debates do not affect our close friendship. Stan has a very wide experience and lends his enthusiasm and support to many colleagues. He is a sought after speaker at meetings, which has helped me by making our joint work widely known.

Progress in science comes through hard work, which is required to explore the multitude of conceivable solutions to a problem. Such studies map out the possibilities and, with some luck, reveal an (in retrospect) obvious path forward. The arguments are then polished and the solution is presented in publications. The accepted methods and results are reviewed in textbooks and courses in a systematic format. The tortuous paths to discovery are left for historians of science to recall. The hidden assumptions underlying an approach can later be very difficult to spot. In the natural sciences progress is often prompted by experiments which reveal phenomena that are not adequately explained by the existing framework.

2. Bound states

Quantum Chromodynamics (QCD) is the generally accepted theory of the strong interactions. The forces between quarks and gluons at short distances ($\ll 1$ fm $= 10^{-15}$ m) are directly given by the QCD action and have been verified in particle collisions with large momentum transfers. Interactions at distances around 1 fm can be simulated numerically ("lattice QCD") and also agree with observations. For reasons that remain poorly understood the strong force does not extend to distances much larger than 1 fm (whereas the electromagnetic force has infinite range). Quarks and gluons are confined in bound states called hadrons, mostly as a quark-antiquark ($q\bar{q}$) pair or as three quarks (qqq). Hadrons are the only QCD states that can propagate over long distances.

The $q\bar{q}$ and qqq classification of hadrons (the "Quark Model") correctly determines their charge, spin and parities. This is similar to the classification of atoms, even though hadrons are much more strongly bound. Unlike in atoms, most of the proton mass arises not from the masses of its quarks but from their binding energy, which is large enough to create many quark pairs and gluons. Hence the Quark Model picture of the proton is simpler than expected.

A Hydrogen atom can be ionized by removing its electron, after which the proton and electron are free to move independently. There is no analogous ionization of hadrons. However violently a quark in a proton is struck by a collision it has never been observed as a free quark. The confinement of quarks and gluons is a qualitatively new phenomenon of great interest, but an explanation based on QCD is lacking.

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[3] Enter the search term: `find author hoyer, paul`

Bound states are not discussed in modern textbooks on Quantum Field Theory (QFT). This is surprising[4], given the enigmas of hadrons and confinement. The attention shifts from the Hydrogen atom in Introductory Quantum Mechanics to scattering phenomena in QFT. This happens surreptitiously, few students or even teachers are aware of it. It took a historian of science to notice the change of topic [16].

Special relativity is built into the Standard Model, and is manifested non-trivially for bound states. The binding energies and wave functions of atoms have been calculated with high precision in the atomic rest frame. No calculations are done in frames where the atom is in motion. In particular, Lorentz contraction is not addressed in quantum physics, even though it receives much attention in classical relativity.

I got a hunch of a QCD method for hadrons shortly before returning to Helsinki from Copenhagen in 1981. I have followed that trail ever since, more intensely in the later years (my hand-written notes are now at 6600 pages. . .). I reviewed my approach in [17]. Overcoming apparent show-stoppers has been encouraging, and it seems strange that I should be essentially alone in this endeavor. From time to time I find myself reviewing the arguments that all this is well motivated. Time will tell.

In Helsinki, on 7 April 2024.

Paul Hoyer

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[4] I have even said irrational, without being contradicted by my colleagues. The problem is not with the textbook authors, but with the lack of material to present.