BIOGRAPHICAL MEMOIRS

Felix Hans Boehm

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A Biographical Memoir by Petr Vogel and Jean-Luc Vuilleumier

An outstanding nuclear experimentalist, Felix Hans Boehm made vital and lasting contributions to many branches of nuclear physics, particularly the application of nuclear techniques to the study of fundamental particle physics problems. His scientific career, lasting more than four decades, spans the evolution of nuclear experiments from brief measurements carried out by a small group of physicists to the present-day endeavors involving large groups of people with varying responsibilities, large and expensive apparatus, long measurements, and complicated efforts to obtain the necessary funding. His career and his achievements illustrate this remarkable transition.

Early Life and Education

Felix Boehm was born into a well-off family in German-speaking Basel, Switzerland, on June 9, 1924, as the second of five sons. With a French-speaking mother, he grew up fluent in both languages. His father's career in the banking and science sectors of publishing, together with Felix's humanities focus in secondary school, gave him a broad and lifelong interest in history and archaeology. He played the flute from an early age and loved classical music throughout his life. Entering his teenage years, he became interested in science and instrumentation, particularly electrophysiology. He managed to get in touch with Nobel laureate Walter Rudolph Hess, a specialist in that field in Zurich, who invited him to participate in research work. Integrated into a small team while still in secondary school, Felix helped to develop an instrument to detect brain waves.

After passing his secondary school exams in 1943, he was ready to go on to university but was instead drafted into the Swiss army. After four months of training, he was deployed along the Rhine River, where he witnessed the retreat of the German army. While still mobilized through the end of World War II, he began studying physics at every opportunity, first at the University of Geneva and finally at the Eidgenössische Technische Hochschule (ETH) in Zurich. He focused on nuclear physics and attended classes in theoretical physics with Wolfgang Pauli and in experimental physics with Paul Scherrer.

After completing his degree in physics in 1948, he joined Paul Scherrer's group, which had built an 8 MeV proton cyclotron. With Pierre Marmier and Jean-Pierre Blaser, he performed several experiments on beta decay and studied (*p,n*) reactions. This was to become the topic of his Ph.D. thesis work, which he defended successfully in 1951 in front of Paul Scherrer and Wolfgang Pauli.[1] Felix stayed on with Scherrer's group as a postdoc, but a visit by Viktor Weisskopf to ETH served as a true source of inspiration, and Felix felt that the action, in physics, was in the United States. He began corresponding with Chien-Shiung Wu at Columbia University about beta decay, and she obtained a fellowship for him to work in her group.

UNITED STATES OF AMERICA

In March 1952, Felix sailed to New York aboard the liner Liberté. While at Columbia, he discovered a new way of doing science. He did work on beta decay, documented in several academic papers. He also found new friends with whom to play music and even accompanied Isaac Stern in a benefit concert of *Symphonie Espagnole* by Édouard Lalo.

After visits to Stanford University and the California Institute of Technology (Caltech), Felix received postdoc offers from both institutions and chose Caltech. In 1953, he crossed the United States in his car, arrived in Pasadena, and joined his former ETH colleague Pierre Marmier in Jesse DuMond's group, traditionally known as Ph-34, in the West Bridge building. Although Felix anticipated that this would be a short-term position, he was to spend the rest of his life at Caltech.

As a postdoc, he helped Jesse DuMond and Pierre Marmier further develop the bent crystal spectrometer, invented by DuMond, to measure x-rays and gamma rays with superior energy resolution. A doubly focusing beta spectrometer had just been added and resulted in an apparatus ideal for investigating nuclear decay schemes. Felix soon began developing his own, often technically challenging ideas, and the group engineer, Herb Henrikson, was of invaluable help to him on his projects. Later on, in 1970, Petr Vogel joined Felix's group, adding expertise in theoretical physics.

In 1956, he met Ruth Sommerhalder at a social event at the Swiss consulate in Los Angeles. They married a year later and had two sons, Marcus and Claude, born in 1960 and 1963, respectively. Felix enjoyed both the social environment and the open atmosphere at Caltech, and following his promotion to assistant professor in 1958, he turned down a job offer from ETH to remain. He was promoted to full professor in 1961, and in 1963, following the retirement of Jesse DuMond, he became head of Ph-34 and found himself in charge of the group's federal grant money. He remained in that position until his retirement in 1995.

The following five sections briefly describe Felix Boehm's most significant scientific achievements, arranged in approximate chronological order. The references there list the most important, or "final," papers corresponding to each section.

PARITY NONCONSERVATION IN BETA DECAYS

Until 1956, it was believed that the "parity symmetry," meaning that the mirror image of every process must be as physical as the original process, is a fundamental symmetry. Following some hints in studies of the K^0 particle decay, Tsung Dao Lee and Chen Nin Yang (winners of the 1957 Nobel Prize in Physics) in that year noted that although such symmetry is observed in the particle production by strong interactions, it was not verified in the decays that involved weak interactions. Hence, they suggested that the parity might not be conserved in such processes. That revolutionary idea was quickly confirmed by the "Wu experiment" involving the β decay of polarized ^{60}Co using a low temperature cryostat, as well as by experiments investigating the μ lepton decay.

Felix Boehm pioneered testing for parity nonconservation without cryogenic apparatus or accelerators needed for muon production. If parity is not conserved, the γ rays following nuclear β decays will be circularly polarized, so it is sufficient to measure the $\beta - \gamma$ correlation and determine the degree of photon circular polarization. Together with Aaldert Wapstra, a Dutch postdoc at Caltech, Boehm built a relatively simple polarimeter and performed tests of parity nonconservation in a number of nuclear β decays, confirming that parity is indeed not conserved.[2] The results convinced Richard Feynman, who was compiling the sometimes-conflicting data available at the time, that the weak interactions are a mix of V and A currents, and this became an important step in the emerging development of understanding weak interactions. It was also an overture for testing the fundamental symmetries using the nuclei as tools.

PARITY NONCONSERVATION AND TIME REVERSAL INVARIANCE IN NUCLEAR TRANSITIONS

Once the vector and axial vector structure of weak interactions was established, the next significant step was the description by Richard Feynman and Murray Gell-Mann, among others, of the current×current form of the weak interaction Hamiltonian. This form also suggested the existence of purely hadronic weak interactions. To test this hypothesis, Felix and his collaborators at Caltech led a worldwide effort to observe a parity nonconservation in nuclear transitions.

This was a challenging task, because the expected effects were tiny, reflecting the relative strength of the strong and weak interactions. The investigation required strong sources, construction of new polarimeters, and techniques to carefully suppress background. In a series of papers published together with his students and postdocs, Felix established limits of about 10^{-4} magnitude for the wrong parity in several medium mass nuclei.[3] In some cases, including in the decay of the 8^- isomer in ^{180}Hf, a positive effect was observed, thus confirming the presence of parity violation in nuclear transitions. In the decades that followed this pioneering effort, many experiments of this type were performed.

Felix's next challenge took on testing the time reversal invariance in nuclear transitions. Until today, the violation of time reversal invariance was observed only in the K meson decays and nowhere else. It is expected, however, that this symmetry is violated also in nuclear transitions at some level. To test this, Felix Boehm used the measurement of the linear polarization of γ rays emitted by polarized nuclei. To achieve polarization, he oversaw the construction of a dilution refrigerator at Ph-34, a rather unique apparatus at that time. Performing the measurement, however, was not the only challenge. The experiment with ^{191}Ir found a positive effect, and it turned out that the same phase angle can arise not only from the time reversal invariance violation but also from the so-called final state effects, caused by the γ interaction with atomic electrons.[4] The observed phase indeed agreed with the expected size of the final state effects. Taking this into account, no time reversal invariance violation was found, but stringent upper limits were derived.

Experiments with Bent Crystal Spectrometers

Because bent crystal spectrometers have an excellent energy resolution for energies corresponding to the atomic K x-rays and γ rays of similar energy, they make it possible to determine tiny energy shifts between two sources that produce radiation of a very similar energy. Together with his student Paul Lee, Felix used bent crystal spectrometers to measure isotopic shifts of the K x-rays for a number of elements and from that deduced the changes in the nuclear $\langle r^2 \rangle$ of the corresponding isotopes. They also measured the chemical shifts between the K x-rays of a given isotope bound in different chemical compounds caused by the rearrangement of the atomic structure owing to changes in the valence electron shells.

Installing a new bent quartz crystal spectrometer at the Los Alamos Meson Physics Facility (LAMPF), Felix and his collaborators performed several innovative experiments, including testing the pionic Ti atom. Pions, spinless particles, obey the relativistic Klein-Gordon (KG) equation, which in the Coulomb field predicts a fine structure splitting, that is, removal of the energy degeneracy between states with the same principal quantum number n but different orbital quantum number l for the bound states. The fine structure splitting corresponding to the KG equation of motion was verified for the first time in this experiment.[5]

Neutrino Oscillations

Neutrinos were long thought to be massless fermions with conserved flavor. The solar neutrino experiment by Ray Davis in the 1970s observed a rate that was two to three times lower than expectations. Harald Fritzsch and Peter Minkowski, at the time in Murray Gell-Mann's group at Caltech, approached Felix and argued that neutrino flavor oscillations that exist only for massive neutrinos might explain the discrepancy and proposed testing this hypothesis at nuclear reactors. Felix discussed the idea with former colleague Rudolf Mössbauer, then a professor at the Technichal University (TU) of Munich, Germany, and director of the Institut Laue-Langevin (ILL) in Grenoble, France, which operates a 57 MW research reactor. Together Felix and Rudolf devised an apparatus to detect reactor neutrinos using the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The positron e^+ was to be detected in scintillators developed at Ph-34. For the neutron n, the chambers were built by a third partner, the ISN Grenoble. TU was in charge of the overall infrastructure. The detector was assembled at a distance of 8.8 meters from the core so that the experiment was sensitive to relatively large differences in neutrino mass squared, Δm^2. Working so far from home was not particularly easy, resources were limited, and unconventional means were sometimes required. One cold and windy autumn day, Rudolf Mössbauer and Felix Boehm were seen in the yard of the mechanical shop wearing white overalls and hard hats, cutting thick polyethylene plates for the neutron shielding themselves because the shop foreman was afraid that polyethylene chips would pollute the building.

This pioneering experiment successfully detected reactor neutrinos, saw no large deficit, and ruled out oscillations with large mixings and relatively large Δm^2.[6] This contradicted findings by the group of Frederick Reines, the discoverer of neutrinos, working at the Savannah River reactor, who had claimed to have evidence for neutrino oscillations, and those findings were later withdrawn.

To extend the sensitivity towards smaller Δm^2, a more powerful reactor was required. Felix Boehm got in touch with Jean-Pierre Blaser, then director of the Paul-Scherrer Institute, who arranged to continue the experiment at the nearby Swiss Gösgen commercial plant. PSI took over the technical support. The e^+ spectrum was measured at distances of 37, 45 and 68 meters from the 2.9 GW core.[7] After correction for the difference in solid angle, the spectra agreed with each other and with expectations. Again a parameter space, with smaller Δm^2, was excluded. And this time it contradicted the results of a French experiment.

By the mid-1990s, the existence of neutrino oscillations was relatively firmly established, with the neutrino mass differences Δm^2 in the range $10^{-2} – 10^{-3}$ eV^2 from the study of the atmospheric neutrinos and a much smaller Δm^2 from the solar neutrino experiment. Both of these findings suggested two relatively large mixing angles. The third mixing angle, today denoted as θ_{13}, remained unknown, however. The best way to determine or constrain this missing piece of the oscillation phenomenology was to use the few MeV energy range of reactor neutrinos and a distance of about 1 kilometer from the reactor core.

Increasing the distance from the reactor core by more than an order of magnitude compared to the existing experiments represented a major challenge, requiring much larger detectors and more efficient background suppression. To meet this challenge, Felix established a collaboration with physicists from Stanford University, the University of Alabama, and Arizona State University. After overcoming considerable bureaucratic and funding difficulties, he found a site at the Palo Verde Nuclear Power Station, which has three identical reactors with a total power of 11.63 GW. Overcoming the background as much as possible in the flat countryside required the construction of a shallow underground site, 890 meters from two of the reactors and 750 meters from the third. The collaboration built a segmented detector with 11.36 tons of Gd loaded liquid scintillator and operated it for 350 days. The results excluded the oscillation mode $\bar{\nu}_e \rightarrow \bar{\nu}_x$ for $\sin^2 2\theta > 0.17$ and $\Delta m^2 > 1.1 \times 10^{-3}$ eV^2.[8] This was an important finding demonstrating, together with the analogous Chooz experiment, that the third mixing angle is considerably smaller than the other two, and the structure of the neutrino mixing matrix became much clearer. The tradition that began with Felix's ILL experiment continues. The mixing angle θ_{13} has since been accurately determined with the next generation reactor experiments Daya-Bay, Double Chooz, and Reno, and the KamLand experiment has confirmed solar mixing.

DOUBLE BETA DECAY

Neutrinos, neutral fermions, can be either distinct from the corresponding antineutrinos (Dirac fermions), or they can be Majorana fermions, identical with the corresponding antineutrinos. Neutrino oscillations show that neutrinos have a nonvanishing mass, making the difference between these two possibilities observable, at least in principle. The neutrinoless double beta decay, $(A,Z) \rightarrow (A,Z+2) + e^- + e^-$, is forbidden with Dirac neutrinos but may occur with Majorana neutrinos, and the decay rate is proportional to the square of an effective mass constructed from the mass eigenvalues and the mixings.

The possibility of exploring Majorana masses had long been recognized. Felix Boehm realized that a widening selection of low-activity materials for detector construction and improved detection methods could lead to lower backgrounds and better sensitivities. As a first step, following a scheme initiated by Ettore Fiorini, a 90 cm^3 detector with ^{nat}Ge was built and operated at Ph-34. The sensitivity was limited, however, by the background from the cosmic rays. Again Felix Boehm turned to PSI, as well as to Neuchâtel, which had been joined by one of his former postdocs, Jean-Luc Vuilleumier. They proposed to set up a small lab in a side cave of the St. Gotthard road tunnel in Switzerland, where the cosmic rays are highly suppressed.

The experiment continued there and yielded good limits for a particular decay mode with emission of a Majoron, but the small size did not allow a good sensitivity to the main mode. The detector did, however, become an invaluable tool for selecting radiopure materials for next searches, first with an array of eight ^{nat}Ge crystals with a total of 1095 cm^3 in a single copper cryostat operated in the St. Gotthard lab. With that, much more constraining upper limits were obtained on the effective mass.[9] Moreover, using the crystal with the best noise, stringent (at the time!) upper limits on cold dark matter were obtained.[10] Thanks to the high natural abundance in ^{73}Ge, the sensitivity to dark matter with spin dependent interaction was particularly high.

Looking at the pioneering work of David Nygren on the time projection chamber, Felix Boehm realized that such an instrument, allowing for three-dimensional imaging in a large volume, would provide an improved event selection, and thus an even better sensitivity. At Ph-34, a prototype 180-liter active-volume TPC filled with xenon at 5 atmosphere was built and tested. Subsequently it was moved the St. Gotthard lab, upgraded, and filled with xenon enriched in ^{136}Xe. Felix spent several weeks on site setting up the experiment while lodging in an apartment near Airolo with the rest of the installation team. Ruth Boehm accompanied him and cooked for the entire company. The experiment ran for several years and provided a new lower limit for the half-life of $T_{1/2} > 3.4\times10^{23}$ yr from which an upper bound on the effective neutrino mass was derived, the most constraining at the time.[11]

A LIFE DEVOTED TO SCIENCE

During his long career, Felix Boehm earned many honors. In 1980, he was awarded the Humboldt Prize from the Alexander von Humboldt Foundation. In 1983, he was elected to the National Academy of Sciences, and in 1985 he became the William L. Valentine Professor at Caltech. In 1995, he was awarded the Bonner Prize in Nuclear Physics from the American Physical Society.

Naturally, Felix Boehm helped launch or advance the scientific career of many of his students, postdocs, and collaborators. Here we name just a few whom we have known personally and who were greatly influenced by the lessons learned at Caltech, with apologies to those that are not mentioned: Mark Chen, Peter Fisher, Edward Lipson, Paul Lee, James Miller, Andreas Piepke, James Thomas, David Wark, Henry Tsz-King Wong, and Alex Zehnder.

Perhaps most important is the influence Felix had on all those who got the privilege to work with him. His way of doing science was an example to all: identifying early on important issues to address, finding the most appropriate experimental methods with his collaborators, keeping an open mind, and pursuing the effort with great resolve until the goal was achieved, behaving at all times like a gentleman. In person and through texts like *Physics of Massive Neutrinos*, which he wrote with Petr Vogel, Felix has inspired and shaped the field of nuclear physics.[12]

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