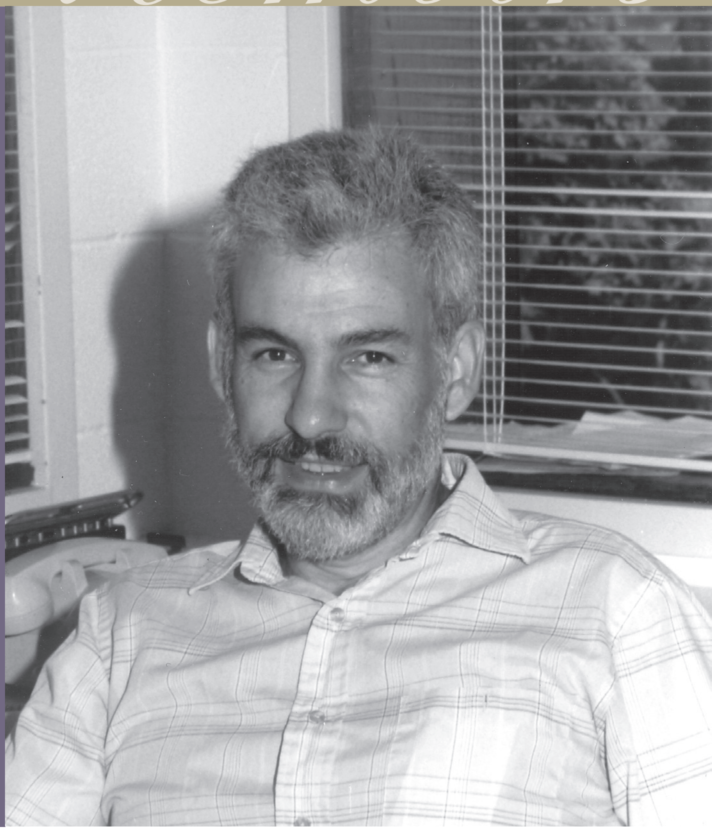
Bruce Winstein

1943–2011

BIOGRAPHICAL *Memoirs*



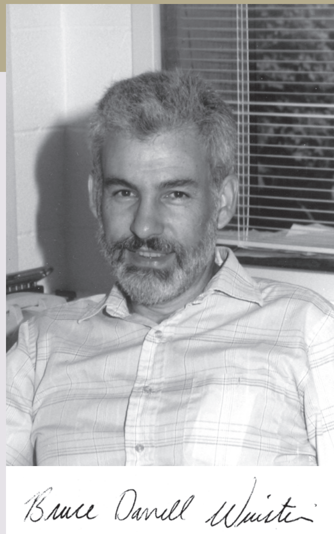
A Biographical Memoir by
Melvyn J. Shochet
and Michael S. Turner

NATIONAL ACADEMY OF SCIENCES

BRUCE DARRELL **WINSTEIN**

September 25, 1943–February 28, 2011

Elected to the NAS, 1995



By Melvyn J. Shochet and Michael S. Turner

Bruce D. Winstein began his career as an experimental high-energy physicist and became renowned for making the most precise measurements of *CP* ("charge parity") violation in the neutral *K* meson system. His results illuminated the tiny asymmetry between matter and antimatter that is essential for the existence of matter in the universe. He was associated with the University of Chicago from 1972 until his death in 2011, first as a senior research associate and finally as the Samuel K. Allison Distinguished Service Professor. Late in his career Winstein became a cosmologist, focusing on the polarization of the cosmic microwave background (CMB) radiation. Bringing to cosmology the techniques from high-energy physics, he made highly accurate measurements of CMB polarization. Winstein was also instrumental in establishing the Kavli Institute for Cosmological Physics at the University of Chicago. Outside of physics, he was an avid fan of avant-garde film, twice teaching a course on the films of Michelangelo Antonioni.

Early years

Bruce was born in Los Angeles, CA, to Saul and Sylvia Winstein. His father was a distinguished physical organic chemist, elected to the National Academy of Sciences in 1955 and a faculty member at UCLA from 1941 until his death in 1969. Carolee Winstein, his younger sister and now a professor in the Division of Biokinesiology and Physical Therapy at the University of Southern California, said that as far back as she could remember, Bruce was "an independent thinker, self-confident, perceptive, and with a mind of his own." She told a story of the 10 or 11 year-old Bruce, upon his parents returning home from a neighborhood party and slightly tipsy, calling the police to report that something was wrong. All ended well, and this incident illustrates the self-confidence that would characterize his career as a scientist.

Bruce attended public schools in Los Angeles: University Elementary School, Paul Revere Junior High, and University High School. His interests were broad and fueled by a great curiosity for how things worked. Beyond his attraction to math and physics and early aspirations to become a chemist, he was an avid reader who loved world literature and discovered Camus and existentialism as a teenager.

Like many other physics graduate students of his generation, Bruce's hero was Richard Feynman, and Bruce sought to work with him in theoretical physics. While this was not to be, he did spend a lot of time with Feynman and established a lifelong friendship.

Following in the footsteps of his father, Bruce did his undergraduate studies at UCLA, not even bothering to apply elsewhere. It took one summer working in his father's lab to discover that he was not a chemist, and while a junior he considered dropping out altogether and becoming a California "beach bum." But as Carolee recounted, Bruce never did anything in his entire life half-seriously; he either was totally uninvolved or he was all in with full enthusiasm, whether it was science, music, film, or running marathons. It would have been interesting to see how he would have approached that vocation, but fortunately for science the urge to be a beach bum passed.

Bruce graduated from UCLA in 1965 with a BA in physics and math, and he was accepted both by Caltech and MIT for graduate studies in physics. At first he chose MIT, but after doing so he had a last-minute change of heart and was able to attend Caltech (where his father had done his doctoral work). Struggling with important issues and gathering as much information as possible before committing to a course of action—sometimes even reversing an initial decision, if more evidence indicated the need—would characterize Bruce's approach to decision making throughout his life.

Like many other physics graduate students of his generation, Bruce's hero was Richard Feynman, and Bruce sought to work with him in theoretical physics. While this was not to be, he did spend a lot of time with Feynman and established a lifelong friendship. In fact, Bruce was with him the day he won the Nobel Prize, accompanying him as he often did to Hughes Research Labs in Malibu where Feynman was giving lectures on topics including cosmology. Around this time Feynman was famous for frequenting (and defending in court) a topless bar in Pasadena, and Bruce accompanied him there at least once—to talk about physics, of course.

Bruce did his Ph.D. work in the Synchrotron Lab at Caltech under the supervision of high-energy physics (HEP) experimentalist Clem Heusch. In a talk he gave at the scientist's 70th birthday party, Bruce thanked Heusch for "rescuing" him from theoretical physics. At Caltech Bruce worked alongside other up and coming HEP experimentalists, including Charlie Prescott, Eliot Bloom, Leon Rochester, and Kirk McDonald. Under Heusch's supervision, Bruce's Ph.D. topic involved measuring the polarization of the recoil proton in the photoproduction of eta mesons. (Polarization was a theme to which Bruce would return in his second career as a CMB cosmologist.)

Bruce with his son Keith and daughter Allison.

Bruce developed an enduring passion for film while at UCLA, amassing a huge collection of movie posters and other memorabilia that included original reels of Marx Brothers, Charlie Chaplin, and W. C. Fields movies. At Caltech, Bruce's interest in avant-garde cinema blossomed, and with Niles Puckett and Kirk McDonald he started the Cinematech to bring independent and experimental films to the Caltech community.

Bruce became particularly fond of the films of Michelangelo Antonioni, gaining enough expertise to twice teach a course on Antonioni's films at the University of Chicago. Earlier, in 1969, Bruce visited the Death Valley set of the director's *Zabriskie Point*. In 2007, shortly before Antonioni's death, Bruce met with him in Rome. As much as he had a passion for understanding how things worked, Bruce had an equally strong attraction to ambiguity, one that found an outlet in his love of avant-garde cinema.

While at Caltech, Bruce lived in the Keck graduate house, where he was the resident Frisbee master, had many friends, and pursued numerous interests outside of physics. He enjoyed hiking in the Sierras, and climbed his first 14,000-foot peak (Mt. Evans) in Colorado. In 1969, when Bruce was finishing up his Ph.D. work, his father Saul died of a heart attack at the very young age of 57. This had a big impact on Bruce, focusing his attention on reducing life's stresses, eating well, maintaining physical fitness (including the running of marathons), and, most important, spending time with family. Years later, almost every summer he and his family went to Rocky Mountain National Park to hike and spend a week or two together in the mountains.

Bruce the high-energy experimentalist

Bruce's first position following his Ph.D. was as research scientist at the Max Planck Institut für Physik und Astrophysik in Munich. Shortly before that time, the SLAC deep-inelastic scattering experiments, and their interpretation using Feynman's parton model, had greatly reinforced the proposition that protons and neutrons were composed of fractionally charged quarks. The first hadron-hadron collider, the Intersecting Storage Rings (ISR) under construction at CERN, would increase the quark search mass range over those at existing accelerators at CERN or Fermilab by a factor of four. Bruce and a few colleagues submitted a proposal to carry out a search as soon as the ISR started operation using a simple but effective apparatus to be placed in an experimental area whose major experiment wouldn't be ready for installation that early. They achieved their sensitivity goal but of course did not observe free quarks (Fabjan et al. 1975). The cross section upper limit was more than a factor of 100 lower than previous results in the 5-20 GeV mass range, which came from cosmic ray experiments.

In fall 1972 Bruce accepted a senior research associate position in Valentine Telegdi's group at the University of Chicago. Four years later he joined the Chicago faculty, of which he remained a member for the rest of his career. Early in 1976, Bruce gave the inaugural Arthur H. Compton Lectures at Chicago's Enrico Fermi Institute; the series consisted of 10 lectures given on Saturday mornings to a broad audience drawn from the city's metropolitan area. Bruce's lectures addressed the question, "What's interesting about elementary particles?" His lectures were well received, and the subsequent series, now established for almost four decades and presented twice a year, remains very popular with the public.

When Bruce joined the Telegdi group, interest in neutral *K* mesons was still at its peak largely because of the surprising discovery eight years earlier of a matter-antimatter asymmetry in those particles' decay (*CP* violation) (Christenson et al. 1964). The group had been carrying out a series of *K* meson experiments at the Argonne National Laboratory's ZGS accelerator, and shortly after Bruce arrived at Chicago the group ran the last of those experiments—a precision measurement of the lifetime of the short-lived neutral *K* meson (K_S), which confirmed recent results that differed significantly from the previously accepted value (Aronson et al. 1976).

When that data run ended, the apparatus was moved to the new National Accelerator Laboratory (later renamed Fermilab) so that the studies could be extended to much higher-energy K mesons. The first experiments studied regeneration, a purely quantum-mechanical phenomenon that can be explained as follows: There are two neutral K meson states that propagate in free space, the K_S and the long-lived K_L. Both are linear combinations of the particles produced in the accelerator-beam collisions, the K^0 and its antiparticle the $\bar{K}^0$. In a long beam of neutral K mesons, the K_S's quickly decay, leaving only the K_L's at the end of the beam. If the beam then passes through material, called a regenerator, the K^0 and $\bar{K}^0$ components of the K_L interact differently because the regen-

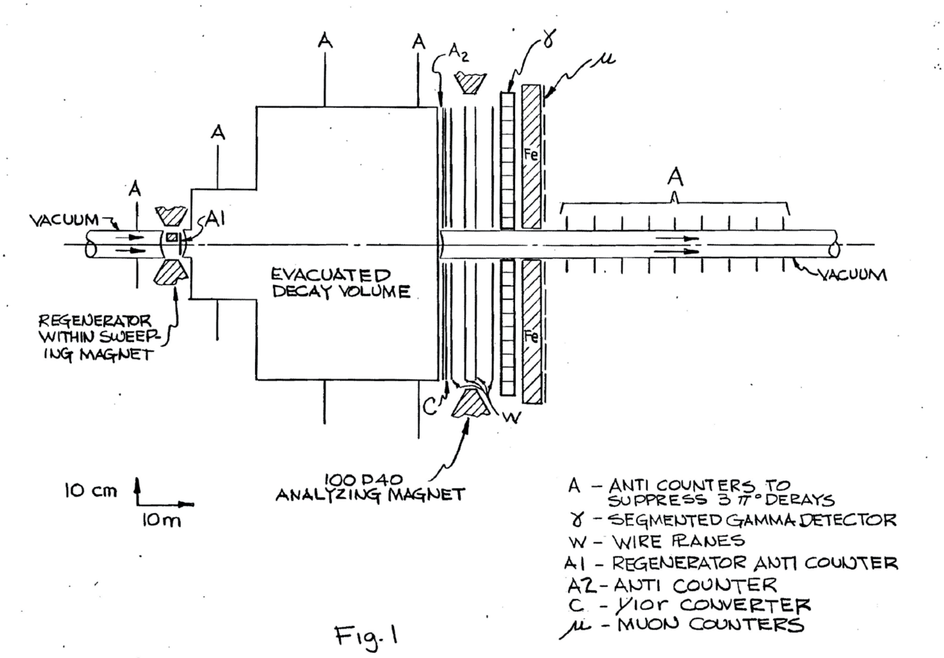


Figure 1. Sketch of the two-beam design from the proposal for experiment 617 at Fermilab. The two beams are shown as the arrows on left side. The regenerator, just to the left of the evacuated decay volume, was moved from one beam to the other after each accelerator pulse.

erator contains only matter. That changes the quantum-mechanical admixture, creating a component of K_S in the previously pure K_L beam, thereby "regenerating" K_S's.

During this period, Telegdi left Chicago for Zürich, and Bruce became the leader of the group. A major source of systematic uncertainty in the *K* meson experiments came from determining the flux of the beam striking the regenerator. Bruce had an ingenious idea, the double-beam technique, to greatly reduce this problem, and that idea proved essential to all future experiments he carried out at Fermilab. Traditionally, a beam of particles was produced by the accelerator's proton beam striking a target, with the resulting secondary beam passing through an opening in a collimator to define the beam size. Bruce had a collimator built with two closely spaced openings. The result was two nearly identical side-by-side beams entering his detector (see Figure 1). The regenerator was placed in front of one of the beams; the other beam provided the measurement of the incident beam flux. The overall particle rates in the detector, and thus the detector performance, were the same no matter which beam an observed *K* decay came from. To remove the dependence of a measurement on the slight difference between the fluxes in the two beams, the regenerator was moved from one beam to the other every 10 seconds, during the time between accelerator beam spills. The detector fed by the double beam obtained a number of results on regeneration. For example, from the measurement of regeneration off of electrons, they were able to determine the charge radius of the K^0, which agreed in sign and magnitude with predictions of the quark model (Molzon et al. 1978).

Bruce was fascinated with the problem of violation, in particular its origin. In neutral *K* meson decay, there are two possibilities. One is that the K_S and K_L are not pure *CP* eigenstates, *CP*-even for the K_S and *CP*-odd for the K_L. Rather, each could have a slight admixture of the opposite *CP* state. If this were the only source of *CP* violation, dubbed indirect *CP* violation, it could be due to a force much weaker than the usual weak interaction (Wolfenstein 1964). The other possibility, direct *CP* violation, would arise when *CP* conservation is violated in the decay of the *K* meson into two π mesons, a process mediated by the weak interaction.

Experimental observations until this time were consistent with the first possibility, with direct *CP* violation contributing no more than 5 percent of the effect. But there was no way to estimate precisely how large direct *CP* violation might be. This changed in the late 1970s, when the discovery of the *b* quark brought attention to a proposal made several years earlier: if there were six kinds of quarks, then the matrix that mixed the quark-type eigenstates into the eigenstates of the weak interaction would have a complex phase that, if nonzero, would produce *CP* violation (Ellis, Gaillard, and Nanopoulos 1976; Kobayashi and Maskawa 1973). Kobayashi and Maskawa were awarded the 2008 Nobel Prize for this proposal. Direct *CP* violation could thus be estimated, and it was small—less than 1 percent of the indirect *CP* violation effect, which itself was tiny, about a 0.2 percent admixture of the opposite *CP* state in the K_L.

Bruce and collaborators designed an experiment that would be sensitive to direct *CP* violation at the then-predicted rate. Because the effect would be so small, and the control of systematic uncertainty so important, they used a scheme, successfully employed earlier in direct *CP* violation searches, called the double ratio method. The ratio of the rate of K_L decaying into two neutral π mesons to that of K_S decaying into two neutral π mesons measures the strength of *CP* violation because the former is forbidden by *CP* symmetry while the latter is not. A similar ratio when the *K* decays into a positively charged π meson and a negatively charged π meson would differ from the ratio using neutral π mesons only if there is direct *CP* violation. Measuring the ratio of these two ratios has the enormous experimental advantage that many systematics cancel, including those from the beam flux, the fraction of K_L's that become K_S's in the regenerator, and the detector efficiencies for the neutral pion and charged pion decays.

There was one additional source of systematic uncertainty that could prevent the experiment from achieving the needed sensitivity. The radiation level in the detector could vary, depending on whether or not a regenerator was in the beam, and the performance of the detector could worsen as the radiation increased. Bruce realized that his double-beam technique would solve this problem. With a regenerator in front of only one beam, K_S decay and K_L decay would be measured simultaneously—the K_S decays from the beam with the regenerator and the K_L decays from the beam with no regenerator. Thus the radiation level in the detector wouldn't depend on which beam a particular decay came from.

Bruce first presented the results of the new experiment in June 1984 at the 11th International Conference on Neutrino Physics and Astrophysics in Dortmund, Germany, a meeting that was broader than its title implied. The new measurement had an uncertainty that was a factor of 3.5 smaller than in previous experiments and was consistent with no direct *CP* violation (Bernstein et al. 1985; Winstein 1984). However, in the intervening few years since the experiment was proposed, the theoretical prediction had dropped by a factor of 4. As a result, the 6-quark model of *CP* violation could neither be confirmed nor excluded. The problem was not primarily systematic uncertainty, which had been adequately controlled, but rather the number of decays that were observed. A much higher-statistics experiment was needed to confront the smaller predicted size of direct *CP* violation.

To achieve this goal, Bruce and his colleagues devised a new experiment. The doubling of the proton beam energy with Fermilab's new superconducting accelerator, the Tevatron, was expected to increase the flux in the *K* meson beam by a factor of 5. But even that was insufficient. To further increase the experiment's statistics, the detector was redesigned with a geometric acceptance also increased by a factor of 5. With a factor-of-25 more detected *K* decays, the statistical uncertainly could be reduced by as much as a factor of 5, which would be sufficient if the predicted rate of direct *CP* violation remained unchanged.

Another experiment, with a different plan for controlling systematic uncertainty, was being constructed at the CERN laboratory in Geneva, Switzerland. Both experiments had a sensitivity goal of 0.1 percent in the ratio of the direct *CP* violation amplitude to that of indirect *CP* violation. With such an important scientific question being addressed, it was imperative to have two independent determinations. The two groups were to be strong competitors until the final resolution of the problem more than 15 years later.

The CERN team reported a preliminary result at the 1987 International Symposium on Lepton and Photon Interactions at High Energies in Hamburg, Germany. The direct *CP* violation amplitude was in the range predicted by the 6-quark model, but the measured value was only 2.4 standard deviations above 0, so the result was inconclusive. At this time, Bruce's team had completed the analysis of its first short data-collection period, and its result was also insufficiently precise to determine whether or not there was direct *CP* violation (Woods et al. 1988). A month later the CERN group, having completed its analysis, published its own result (Burkhardt et al. 1988). CERN's measurement was now a 3-standard-deviation effect, so the paper reported evidence for direct *CP* violation. A year and a half later, Bruce and his collaborators had finished analyzing 20 percent of the sample they would eventually acquire and published their null result (Patterson et al. 1990), reporting that it "does not confirm recent evidence for direct *CP* violation." This was seen as an important disagreement that had to be resolved, even though the difference in the results of the two experiments was less than 2 standard deviations.

After three more years, both experiments had completed full data-taking and published their results (Barr at al. 1993; Gibbons et al. 1993). The Fermilab result went up a bit and the CERN result came down a bit, all consistent with their previous results. The difference between the two measurements was now only a little more than one standard deviation, but whether there was direct *CP* violation or not was still not clear. Yet more precision was needed, so both teams designed new experiments.

Bruce's group made significant improvements in its detector, including a much higher-resolution electromagnetic calorimeter to better separate $K_L \rightarrow \pi^0\pi^0$ decays from background and a fully active regenerator to identify inelastic scattering. The data were taken in 1996–97, and for the first time in a *CP* violation experiment the analysis was "blind" (the result was shifted by an offset unknown to the experimenters until the analysis was complete); a paper on the first quarter of the data was published in 1999 (Alavi-Harati 1999). The result was unequivocal; direct *CP* violation was seen with a significance of almost 7 standard deviations. The problem that Bruce had been attacking for 15 years was now resolved.

When the European experiment reported its result later that year, it was consistent with Winstein team's value (Fanti 1999). A question that was explicitly addressed in the Fermilab paper was why the researchers' earlier experiment had obtained a null result. They went back to that analysis and thoroughly checked it carefully, but could not find "any explanation for its lower measured valued other than a possible, if improbable, fluctuation." But if we compare the 1990 result with the current precise world average for the ratio of the direct *CP* violation amplitude to the indirect *CP* violation amplitude, we find that the early Winstein result was only low by a little more than one standard deviation—a fluctuation indeed, but not so improbable.

For Bruce's leadership in precision measurements of the properties of neutral *K* mesons, most notably the discovery of direct *CP* violation, he was a co-recipient of the American Physical Society's 2007 W. K. H. Panofsky Prize in Experimental Particle Physics. He had been elected to the NAS in 1995 for "his comprehensive study of the important and puzzling phenomena of *CP* violation," and he was elected to the American Academy of Arts and Sciences in 2007.

The intellectual drive for this long series of experiments came from Bruce's desire to learn more about the mechanism of *CP* violation. And the collected data proved to be extremely rich, resulting in some 80 papers in the *Physical Review*. They included studies of rare *K* decay and the search for forbidden channels, tests of *CPT* symmetry, and precision measurements of the properties of many decay modes. A measure of the advances made during the period of Bruce's *K* meson experiments was the number of

$K_L \rightarrow \pi^0\pi^0$ events observed. Experiments done in the early 1970s each observed about 100 of these *CP*-violating decays; his final paper on this subject (Alavi-Harati 2003) reported over three million of them!

Such statistics demanded an extraordinary control of systematic uncertainty. The hallmark of Bruce's experiments was a detailed understanding of his detector's performance at the level of a part per mil or better, which is what enabled him to limit systematics to the required level. This motivated the legendary frequent phone calls that Bruce made in the middle of the night to the physicist on shift at the experiment—whether it was a graduate student, a postdoc, or a senior faculty member—to ask detailed questions about the performance of the detector and the quality of the data.

Bruce was a wonderful mentor of students and postdocs. During his series of *K* meson experiments, he had 14 graduate students, of whom six are senior faculty members at large research universities, three are senior staff members at national laboratories, and five are in a variety of fields in the private sector.

With the conclusive observation of direct *CP* violation, Bruce knew that little more would be learned about its source from studies of *K* decay. The center of *CP* violation investigations had moved to the enormous collaborations at SLAC in California and KEK in Japan that were studying the decays of mesons containing *b* quarks, in which much larger *CP*-violating effects were expected. Bruce preferred smaller collaborations carrying out experiments that he designed. To continue doing that he had to look to other important and challenging scientific questions, and he found them in cosmology.

Bruce the cosmological physicist

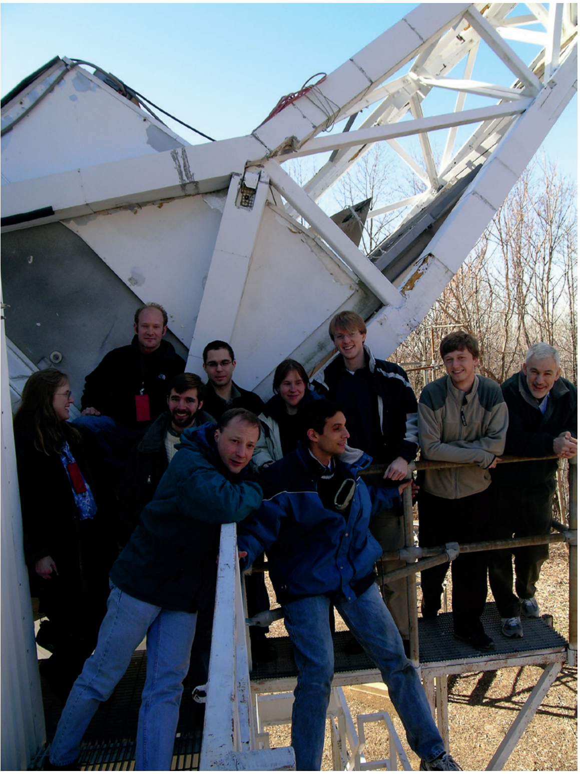
Bruce's intellectual home at Chicago—the Enrico Fermi Institute—not only provided a stimulating environment for his work but also exposed him to other fields, including the revolutionary coming together of particle physics and cosmology, led by his colleagues David Schramm and one of us (MST). While not everything in cosmology was to his liking—especially the more astronomical aspects involving telescopes and stars—the cosmic microwave background (CMB) was very much to his liking. The CMB, which is the 2.726 K blackbody radiation left over from the hot big bang, holds a wealth of information about the universe—age, contents, and earliest history—that can be measured by the precision high-energy-physics techniques with which Bruce was so familiar.

In 1992 NASA's COBE satellite detected the long-sought, small variations (one part in 10^5) in the intensity of the CMB, known as the anisotropy, that provides a map of the universe at a simpler time—380,000 years after the beginning—before stars, galaxies, and all the other messy things of astrophysics existed (Wright et al. 1992). The race was now on to map CMB anisotropy on finer and finer angular scales to reap the harvest of information contained therein. Bruce's Chicago colleague Stephan Meyer was a member of the COBE team, and John Carlstrom had recently arrived at Chicago with ambitious plans to measure the anisotropy and its polarization at the South Pole.

The CMB is polarized at the few-percent level—a key prediction of the big bang theory—and a mode of the polarization, the odd parity or B-mode, is produced by gravitational waves generated during inflation (Kamionkowski, Kosowsky, and Stebbins 1997; Seljak and Zaldarriaga 1997). Detecting the B-mode signature is a fundamental test of inflation, and the amplitude of the B-mode signal pins down the energy scale and time of inflation. Inflation-produced B-mode CMB polarization was—and remains today—the biggest prize in cosmology.

Unfortunately, there was, and is, no clear theoretical prediction for the amplitude of the B-mode signal. Moreover, the difficulty of the task of detecting it is enormous—a measurement at the level of a part in 10^7 or better, or in terms of a temperature variation, less than 300 nanoKelvin in a 300K world. Important and very hard to do, and add to that, the skills and techniques of HEP he could bring to bear, detecting the B-mode signature of CMB polarization had Bruce's name all over it.

Bruce was as methodical in his approach to the CMB as he was with *K* mesons. First, he would have to educate himself. He decided to do so by taking a sabbatical at Princeton University and working with a CMB group there. This may seem odd given all the expertise at Chicago, but Bruce didn't just want to participate in important science, he wanted to lead an experiment and make important discoveries. If he had gotten involved at Chicago, he would probably be a follower, not a leader. By going to Princeton he could get the experience needed to mount and lead his own experiment. During his 1999–2000 sabbatical Bruce worked with Suzanne Staggs's group on the PIQUE CMB (PIQUE for Princeton IQU Experiment, where I, Q, and U refer to the Stokes parameters that characterize the polarization). This small experiment on the roof of the physics building operated at 90 GHz (and later 40 GHz) for about two years. PIQUE set a limit on the E and B mode polarization at an angular scale of about 1 degree of 10 microKelvin. No detection, but good training for the new cosmological physicist.



The CAPMAP telescope and team.

When Bruce returned to Chicago he was ready for bigger things. He began to establish himself as an important new player in the CMB community, serving on committees, giving review talks about the CMB, and lecturing on it at summer schools. He also saw an opportunity to give more coherence to the existing and still growing cosmology activities at Chicago and Fermilab. The Physics Division of the National Science Foundation had announced a new program—the Physics Frontier Centers (PFCs)—that would fund a large-scale activity in a physics frontier at the level of several million dollars per year for five years. Bruce organized Chicago's proposal effort, which was successful. In September 2001, the Center for Cosmological Physics (CfCP) at Chicago came into existence, with Bruce as its director. (For a newcomer to cosmology, this was an impressive success given the competition—including Princeton—but it was not a surprise to Bruce, who said that in his entire career only one proposal of his had been turned down.) In 2004, the CfCP was endowed by the Kavli Foundation and became the Kavli Institute for Cosmological Physics (KICP), the third Kavli Institute. Bruce served as its first director and got it off to a strong start.

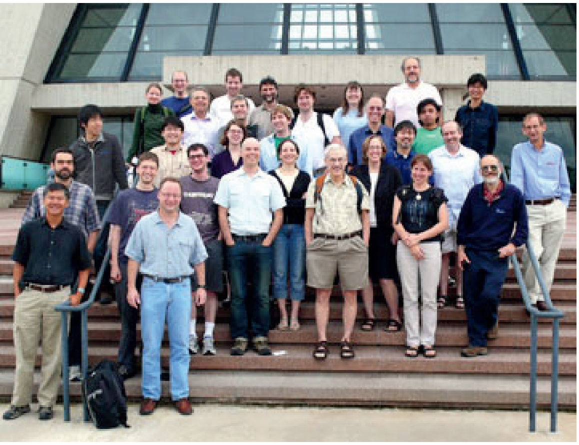
The centerpiece of Chicago's PFC—and Bruce's pride and joy—was the group of 10 KICP Fellows who were free to work with any of the center's 12 or so faculty. Many of the Fellows chose to work with Bruce on CMB polarization; Bruce's recent conversion to cosmology in fact attracted several talented fellows who had done their Ph.D.s in high-energy physics. The PFC also funded workshops, conferences, and visitors, for a few days to year-long sabbaticals, and it seeded new projects, not just in CMB but also dark matter and dark energy experiments. For the four years that Bruce was director of the CfCP/KICP he devoted his full time and energy to making the new center successful. Today, the KICP thrives as a national cosmology center, especially in the area of CMB cosmology.

The QUIET telescope at its 17,000-ft site in Chile's Atacama Desert.

Bruce's real passion was his new science focus, CMB polarization. And he had local competition—John Carlstrom, Stephan Meyer (who was involved in NASA's WMAP [Wilkinson Microwave Anisotropy Probe] satellite), and a young assistant professor named Clem Pryke whose BICEP2 (Background Imaging of Cosmic Extragalactic Polarization) experiment would eventually make the first direct detection of the B-mode polarization signal. Carlstrom's DASI (Degree Angular Scale Interferometer) experiment at the South Pole made the first detection of CMB polarization signal in 2002; he and his colleagues detected the even parity or E-mode polarization that arises due to density perturbations rather than from gravitational waves (Kovac et al. 2002). However, the Holy Grail—the B-mode signature of inflation—was still out there to chase.

PIQUE became CAPMAP (Cosmic Anisotropy Polarization MAPper), a more ambitious project with 12 W band (~90 GHz) and 4 Q band (~40 GHz) polarimeters operating on a 7-meter antenna at Lucent Labs in Crawford Hill, NJ. The first sentence of the first CAPMAP paper summarized what Bruce believed: "The CMB is arguably the most fruitful source of cosmological information." In 2008, CAPMAP published very significant detections of the E-mode in the multipole range l = 400 to 1500, competitive with results of DASI, WMAP, and other leading polarization experiments. The upper limits to the B-modes these projects obtained were at the few microKelvin level.

Bruce was ready for the assault on the B-modes, with an experiment that he would lead and in a much better site than New Jersey. He brought together researchers from several other collaborations—PIQUE/CAPMAP, CBI (Cosmic Background Imager), and QUaD (for QUEST at DASI, where QUEST stood for Q and U Extragalactic Sub-mm Telescope)—to launch a world-leading CMB polarization experiment: QUIET, for Q/U Imaging Experiment. QUIET operated at two frequencies (40 and 90 GHz) and



The QUIET Collaboration at a Fermilab meeting.

was located in the high (17,000 ft) and very dry Chilean Atacama Desert near the ALMA (Atacama Large Millimeter/submillimeter Array) site.

QUIET published its first results at 40 GHz shortly before Bruce died. In his final months, he worked hard to get the analysis done. The results were notable for a technique he imported from particle physics—blind analysis to avoid any bias, however unintentional. About a year after he died, the results—still upper limits—from the more scientifically powerful 90-GHz band detectors were published (Araujo et al. 2012).

QUIET was a very capable experiment, but not the final assault on the B-modes. Bruce had more ambitious plans—QUIET II—involving more particle physicists and a new funding partner, the U.S. Department of Energy (DOE). However, after his death, the QUIET Collaboration dissolved, as its scientists became involved in other experiments. Nonetheless, Bruce's CMB legacies include the DOE's continued interest in the CMB. In particular, a key part of the current particle physics roadmap (P5 Report) is a Stage IV (S4) CMB polarization experiment.

Since Bruce passed away, there have been several detections of the B-mode CMB polarization. The first were obtained from the gravitational lensing of background E-mode polarization (an important calibrator for and step toward detecting the inflation-produced B-modes) by Carlstrom's South Pole Telescope at multipoles l ~300 to 2300 (Keisler, Crites, and Padin 2015; Hanson et al. 2013), and by the Polarbear (Naess et al. 2014) and ACTPol (Ade et al. 2014) experiments in the Atacama desert. The second detection of B-mode CMB polarization was at l ~ 80 by the BICEP2 Collaboration (Ade et al. 2014). The signal that Pryke and his collaborators detected was consistent with inflationary B-modes, but a joint analysis that cross-correlated the BICEP2 data with Planck Satellite data showed that much—if not all—of the B-mode signal detected was due to galactic dust emissions (Ade et al. 2015). The race for a definitive detection of the inflation-produced B-mode signal continues and, sadly, Bruce is no longer in the thick of it.

BruceFest!

With the exception of one-year sabbaticals at Princeton and Stanford, Bruce spent his entire academic career at the University of Chicago—which was also where he met his wife Joan Drucker Winstein, then a graduate student in Japanese and later a banker. He and Joan were married on February 10, 1979, and their two children, Keith (born in 1981) and Allison (1988) grew up in Oak Park, IL, where the family's home is located. Keith is currently an assistant professor of computer science at Stanford and Allison is a music teacher in the Metropolitan Nashville Public Schools system.

Among other things, the Oak Park home was an audiophile's dream, featuring Bruce's magnificent stereo system and record collection. It also housed in its basement a theatre system for screening art films. Many of us were invited over to listen to music—classical and jazz—and see films that Bruce thought we ought to see. The audio and video recordings were always of the highest quality available, and Bruce's commentary was equally impressive. In the early days of CDs, true to form, Bruce hosted "blinded" comparisons of vinyl and CD audio recordings.

In fall 2007, Bruce was diagnosed with bile duct cancer. For almost three and a half years he and Joan battled the cancer, working with doctors both at the University of Chicago and the M.D. Anderson Cancer Center in Houston, TX. There were highs and lows, but through it all they maintained a high quality of life for Bruce, and he continued to come to the KICP to work on QUIET and plan for QUIET-II. While his visits became less frequent, when he was there he seemed like the same old Bruce, enthusiastic and fully engaged. Many of his colleagues, especially those not in Chicago, did not even know Bruce was ill.

On January 28, 2011, the KICP, Department of Physics, and Enrico Fermi Institute—the three units at Chicago that Bruce dearly loved—held a conference in honor of his retirement, the Bruce D. Winstein Symposium or, simply, "BruceFest!" More than 160 of Bruce's friends and colleagues from around the world came, including his sister Carolee and her husband astrophysicist Kip Thorne, his wife Joan, son Keith and daughter Allison, and Middlebury College professor Ted Perry. Perry, a Winstein friend and the Fletcher Professor of the Arts, gave a beautiful lecture on Michelangelo Antonioni's Surrealist Impulse. The other talks tracked Bruce's scientific career, from *CP* violation in the *K* meson system (colleague Jim Cronin, former student Richie Patterson, and theorist Fred Gilman and experimentalist Konrad Kleinknecht) to cosmology (QUIET/CAPMAP/PIQUE collaborator Suzanne Staggs and one of us, MST).

BruceFest! was a wonderful celebration of an exceptional scientist and beloved friend and colleague. At the dinner Bruce marshaled all of his strength to join us. Feeling weak, he had written remarks for his son to read; instead, at the last minute Bruce gave a moving speech and held court at one end of Ida Noyes Hall for the next hour. Remarkably, after a full day and evening that exhausted all of us, he and Joan had the energy to host a brunch the next morning for the out-of-town guests. After this big event Bruce and Joan traveled to attend their daughter's "senior thesis," a flute recital at Vanderbilt University. On February 28, 2011, precisely one month after Bruce's friends, colleagues, and family celebrated his scientific career, he died peacefully in his sleep.

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