Fall 1988

Fast Track Physics: [Dr. Konstantin Goulianos]

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THE ROCKEFELLER UNIVERSITY

RESEARCH PROFILES

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"It was as though you had fired a 15-inch shell at a piece of tissue paper and it had bounced back and hit you."

—PHYSICIST ERNEST RUTHERFORD (1871-1937) describing his astonishment when alpha particles, fired at a gold sheet a few hundred atoms thick, were deflected, resulting in the discovery that the atom contains a nucleus.

Fast Track Physics

The shadowy image on the screen is sufficiently suspicious for the x-ray technician at LaGuardia Airport to ask the man with the brown box to step to one side. As a uniformed security officer, thumbs in her gunbelt, approaches the inspection table, Professor Konstantin Goulianos has already removed from the box an electronic device encased in a transparent plastic cylinder.

"It's not a bomb, is it?" the officer asks, as the object is placed in her hands. Dr. Goulianos replies with his customary explanation, "Scientific equipment."

The officer nods. She studies the object, peering at it from different angles as if it were a piece of sculpture. Her eyes, tense with suspicion before, open with pleasure as she regards the polished screws, gleaming coils of copper wire, and daubs of solder twinkling on a background of green circuit boards.

What she has not been told is that the instrument will be part of the biggest physics experiment in history, designed to detect the creation of new matter from collisions of subatomic particles at energies never before possible. Finally, she says, "I've never seen anything like it before," and waves him on to the waiting plane.

Once airborne, Dr. Goulianos reflects on the security officer's reaction. "The first rule to remember when building a particle detector," he says, "is that ugly things don't work."

Dr. Goulianos is en route from his laboratory of experimental physics at The Rockefeller University to the world's most powerful atomic particle accelerator—the Fermi National Accelerator

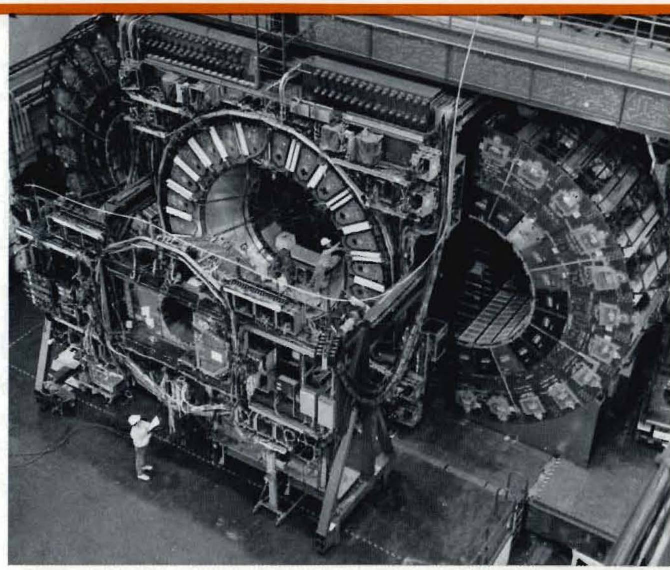
Konstantin Goulianos (foreground) and Sebastian White place a drift chamber inside the beam pipe.

WHERE PARTICLES COLLIDE

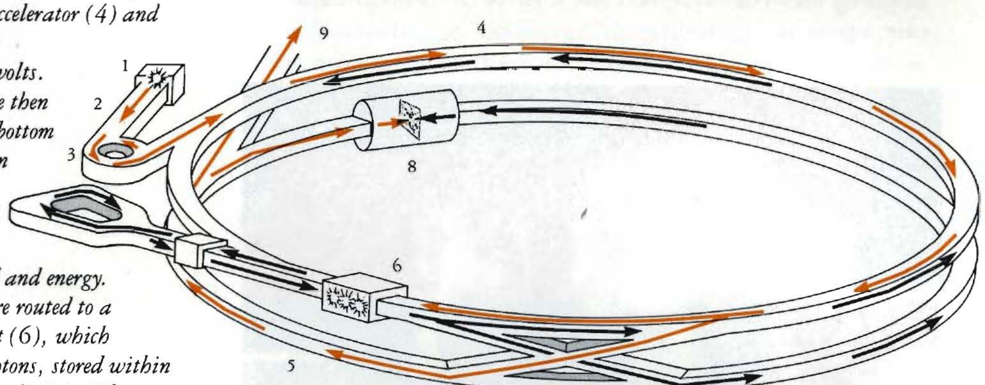
The Tevatron is the final stage in a sequence of five accelerators that propel protons to 99.99994 percent the speed of light with an energy of 1 trillion electron volts.

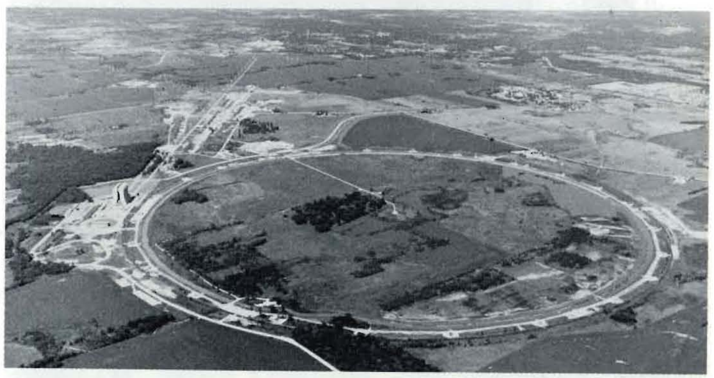
Ions containing two electrons and one proton are generated in a Cockcroft-Walton accelerator (1). At 750,000 electron volts, they are injected into a linear accelerator (2) where they reach 200 million electron volts. At the Booster (3), a rapidly cycling synchrotron 500 feet in diameter, the ions are stripped of their electrons, leaving only protons, which are accelerated to 8 billion electron volts. They are then injected into the main accelerator (4) and whipped to 150 billion electron volts. Some protons are then switched to the bottom tier, the Tevatron accelerator (5), where they achieve their final speed and energy. Other protons are routed to a beryllium target (6), which produces antiprotons, stored within a magnetic "corral" (7). When enough antiprotons have accumulated in the corral, they are released into the main ring. Because of their opposite charge, they travel in the opposite direction from the protons. The two particle beams collide at a point on the ring called B-zero (8), where a series of detectors record and measure the resulting particles and forces. Still other protons are switched magnetically (9) from the main ring to other targets for other kinds of experiments.

From step one to B-zero, protons travel 3 million kilometers in under 20 seconds.



The CDF Central Detector opened up for a maintenance check prior to installation.





Aerial view of Fermilab's four-mile main accelerator ring in which the Tevatron, the world's only superconducting particle accelerator, is housed below ground.

Laboratory, or Fermilab, located in Batavia, Illinois, forty miles west of Chicago. There, subatomic particles called protons and antiprotons, focused by powerful magnets into two counter-rotating beams, will be brought into collision. His device, called a drift chamber, is one of a family of eighteen such instruments built to join an array of other kinds of detectors surrounding the collision area. They will monitor the maelstrom of exotic new particles that will emerge from the clashing beams of protons and antiprotons accelerated to approximately 186,000 miles per second—99.99994% of the speed of light. The experiment, which will run for about a year, involves the contributions of more than two hundred physicists from ten American universities, three national laboratories, and four research institutions in Italy and Japan.

With the detector beside him on the front seat of the rented car, Dr. Goulianos drives under the three-pronged arch spanning the entrance to Fermilab. Beyond the arch lie the lab's high energy physics facilities, built on and under 6,800 acres of Illinois prairie. In the near distance, rising sixteen stories above the flatland, is the laboratory's head quarters, Wilson Hall (named after Robert J. Wilson, Fermilab's builder and first director), the command center for Fermilab's two thousand scientists, engineers, and support staff. The building also provides office space for the Rockefeller team and the other physicist members of the Universities Research Association, a consortium of fifty-four research-oriented universities who use the facility which is supported primarily by Department of Energy funds.

But instead of stopping at Wilson Hall, or the small farmhouse he rents in Fermilab Village a mile or so beyond, Dr. Goulianos follows the road past a series of interlocking fish ponds and a herd of grazing buffalo. Off to the left, near a small wood, is a cemetery where Illinois pioneers rest in the shadow of nondescript laboratory buildings. To the right is Fermilab's centerpiece, the main accelerator ring.

Aboveground, the four-mile circumference of the giant accelerator is outlined by a service road and a moat of water, visible from space, a perfect circle etched into the landscape. Underground a three-meter-wide tunnel houses two of Fermilab's five interconnected accelerators, one on top of the other. The bottom accelerator is called the Tevatron, and it is the final stage of a five-step energy-injection relay that will carry

the protons three million miles in under twenty seconds and charge them with an energy of one trillion electron volts, an increase of three times the energy over the former accelerator champion at CERN, the European Nuclear Research Center, in Geneva, Switzerland.

"The only way to find out about matter is by matter interacting with matter," says Dr. Goulianos. The near light-speed velocities achievable by the Tevatron are due, in part, to a system of superconducting magnets that keep the protons and antiprotons in orbit. Each time they complete a circuit around the ring they are kicked by electrical pulses to ever-higher speeds. The faster the particles hit each other, the more energy is available for production of new matter. When protons are brought into collision with antiprotons circulating in the opposite direction and traveling just as fast, they possess sufficient energy to produce some sixty or so particles of various masses and diverse properties. "Unlike collisions in everyday experience which destroy things," says Dr. Goulianos, "particle collisions lead to the birth of new particles."

MEASURING MISSING ENERGY

Dr. Goulianos parks in front of an enormous, garagelike building adjacent to the ring at its northern perimeter. Although the two particle beams—one carrying bundles of protons, the other antiprotons—are engineered to intersect at six points (lettered A through F) around the ring, collisions can only be observed in detail here, at B-zero. The name of the building at B-zero that houses the central detector and its computer, electronic, and cryogenic hardware has been abbreviated from "Collider Detector at Fermilab" to CDF.

Whereas the package containing Dr. Goulianos's drift chamber is comfortably wedged under his arm, the fifty-million dollar central detector is a two-story, thirty-foot tall cube weighing two-thousand tons. "Although the first thing that amazes one about the CDF is how big it is," says Dr. Goulianos, leading the way into the B-zero facility, "people often miss the idea of how small some of its countless components actually are.

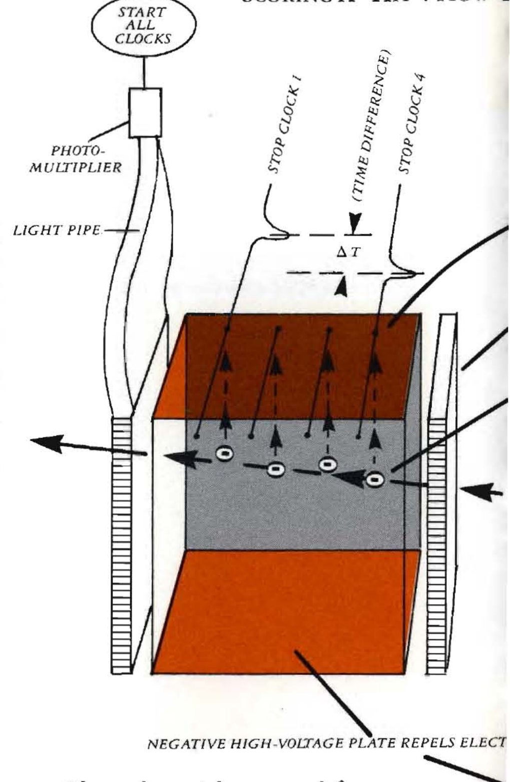
"Particles collide at a rate of about ten-thousand times a second," he continues. "The central detector has one-hundred thousand electronic channels that measure the energy and direction of an average of about sixty particles per collision. Some of these secondary particles last only an instant before they decay into still other particles. The detector must process all the information stored in the one hundred thousand channels at the rate of ten thousand events per second, and must select only a handful of events per second to be recorded on magnetic tape for future detailed examination."

Designed to be a nearly hermetic system, the detectors at CDF act as an energy trap, surrounding the half-meter collision area with a variety of tracking and energy-detecting devices. Some of the particles CDF physicists are looking for can be detected only by their absence—their missing energy. A cardinal rule of physics dictates that the energy flowing out of a collision must be symmetrically balanced. So to find these new particles the energy flow from a specific collision must be precisely determined. No angle (except the direction of the beam) is left unmonitored. No species of particle or measure of energy is ignored. Having established the pattern of the energy flow, any unbalanced or absent energy is a flag to the physicists to look out for "interesting" interactions.

"One challenge of the experiment," says Dr. Goulianos, surveying the activity on the ground floor, where physicists and technicians are testing various components of the giant CDF, "is to design a triggering system that will detect and record those events that are more likely to contain the particles of interest. Out of each ten thousand collisions per second, only a few can be recorded. The trick is to filter out the irrelevant information, but not necessarily the unexpected." Even with the sophisticated electronic screening, several million events will have been recorded after a few days' run. Physicists like Nikos Giokaris and Robert Plunkett, members of Rockefeller's experimental physics group, stay at Fermilab year round to manage the data. Analysis of the data is performed both at Fermilab and at Rockefeller.

From the second floor of the CDF facility, Dr. Goulianos spys, on the floor below, a section of the beam pipe straddling two sawhorses. The pipe has eight circular fixtures attached to it at right angles, two at each end, and four at the center. These are the so-called "Roman pots" in which the drift chambers will be placed. Four technicians from the Italian arm of the collaboration are staring down at the pipe like surgeons discussing an unconscious patient. A problem has arisen with

SCORING A "HIT": HOW T

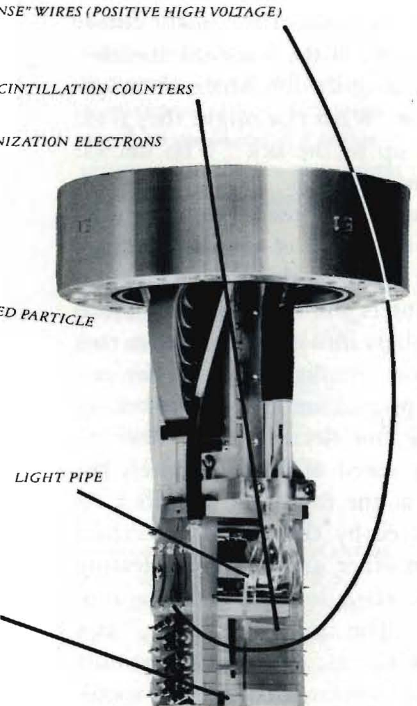


Charged particle scattered from the beam enters drift chamber.

Passing through scintillation counters, the particle triggers an electronic "clock", which produces time value t_0.

The particle collides with argon gas molecules in detector, knocking electrons from their orbit, which "drift" toward positive high-voltage "sense" wires. Accelerated by the high field, they collide with the argon gas molecules causing an electron cascade. The resulting electrical

RIFT CHAMBER WORKS.



pulse stops the electronic clock, producing time value t.

By calculating time differences ($\Delta T = t\text{-}t_0$) between the time the particle enters the drift chamber and the electrons striking the "sense" wires, physicists are able to calculate the particle's angle and trace its origin to a specific collision in the beam pipe.

the mylar sleeve which will line the pots and electrically insulate the equipment inside. The specially formed plastic insert bulges slightly at the bottom of the pot, lifting the detector so that the lid of the pot cannot be sealed properly. Dr. Goulianos, arriving on the scene, determines that the same problem exists for all the pots. After discussions with the leader of the Italian team, a solution is found involving a kind of scotch tape with high electrical strength.

Like most high energy physics installations, the facility at B-zero is a mixture of high and low tech. Not only must all the individual components of CDF work as a unit and perform flawlessly under continuous use, they must also withstand the vicissitudes of the laboratory environment. For example, a bolt is sheared, or a space through which cables are to be strung is discovered to be too narrow. In one instance, a wrench was methodically dropped from varying heights on the beam pipe to test the pipe's durability.

Murphy's Law of particle physics say that the most infinitesimal oversight will come back to haunt you. Since much of the technology was created specially for the CDF experiment, engineers and physicists must work together to learn the idiosyncracies of the new machine.

Placing the drift chambers in the specially designed Roman pots along the beam pipe is a modification of technology first introduced, at the CERN accelerator, by a group from the University of Rome, hence the name. Fingering his luxuriant moustache, Dr. Goulianos jokes that after he's finished with the Roman pots they'll be renamed Greek pots.

EARLY EXPERIMENTS

Growing up amid the sounds of goose-stepping Nazis on the streets of his hometown of Salonika and in the poverty of postwar Greece did not allow "Dino" Goulianos much time for a formal introduction to physics. But even at an early age, he possessed the hands-on curiosity of a born experimentalist. For example, he remembers, as a boy, foraging with a pack of neighborhood children in a machine shop abandoned by the Nazis as they retreated from the city. Among all the treasures, the nine-year-old pocketed a "nice, square looking piece of metal." It turned out to be a magnet and, says Dr. Goulianos, "I've been playing with magnets ever since."

As he was approaching graduation in the Chemistry Department of the University of Salonika, a cousin suggested that he join him in business as a chemist in a tomato-paste factory. An announcement in the local newspaper led instead to a Fulbright scholarship in physics at Columbia University in New York. At Columbia, in 1958, the young neophyte was catapulted into the golden age of physics, and was exposed to many of the field's top theorists and experimenters. His foreign student adviser was Professor Charles Townes, who had invented the laser that very year. Working on his thesis with Professors Melvin Schwartz, Leon Lederman, and Jack Steinberger, he participated in experiments at the Brookhaven National Laboratory that established the existence of a particle called muon–neutrino.* In 1971 he met Rodney Cool, who had just joined The Rockefeller University to establish a laboratory of experimental physics. Dr. Cool asked him to join the laboratory, which began a close and productive association that came sadly to an end with Dr. Cool's death in the spring of 1988.

Dr. Cool conducted his experiments primarily at the CERN facility where he was instrumental in establishing the quark theory of matter. Dr. Goulianos's interests have focused mainly on small angle physics, a class of experiments involving an energy transfer between particles called diffractive excitation. He and his colleagues have designed a variety of experiments for Fermilab, which has become a second home to the team.

"The Rockefeller is able to participate at the forefront of high energy physics because of the way this type of physics is conducted at places like Fermilab," says Dr. Goulianos. "For example, Fermilab's machine shops become an extension of our machine shop, and vice versa. The same is true for computer and electronic capability. We conduct the bulk of our own experiment's R&D on campus, designing, manufacturing, and testing a prototype of, say, an electronic circuit or a particle detector. Then we give it over to Fermilab for mass production. It is highly economical and effective.

"Because of its collaborative nature," he continues, "research at Fermilab is ideally suited for physicists from universities like The Rockefeller who maintain their flexibility and independence." Rockefeller experimentalists have worked, in addition

*Schwartz, Lederman, and Steinberger shared the 1988 Nobel Prize for this experiment.

Konstantin Goulianos and Rodney Cool in 1987.

to Fermilab, at the Brookhaven and Livermore laboratories and, as mentioned previously, at CERN.

Leon Lederman, director of Fermilab, says, "In addition to contributing to the CDF conglomerate as a whole, the thrust of the Rockefeller group has been in the area of small angle physics, an area in which they have been working for many years and in which not enough work is being done generally. It's a unique piece of physics they're doing and, what's more, they're all terrific guys." He smiles, acknowledging his bias. He served as thesis adviser at Columbia University for Dr. Goulianos and later for Sebastian White, another key member of the Rockefeller team.

A DIFFERENT WAY TO MAKE MATTER

Small angle physics refers, in part, to what happens in collisions in which particles strike each other with enough momentum to transfer energy but not enough to change their direction appreciably or trigger a cascade of new particles. In most such collisions (termed elastic) particles are simply scattered in a billiard ball fashion. The collisions of interest to Drs. Goulianos and White are those in which colliding particles maintain their forward direction and in a sense pass through each other, losing a small amount of momentum. The loss of momentum causes one of the particles to be deflected out of the beam and into the line of drift chambers, where its angle is measured. These detectors are able to "see" particles coming out of the beam and measure their angles to an accuracy of one thousandth of a degree.

"Now here is the miracle," Professor Goulianos explains. "If one particle loses momentum, the other must balance the loss by losing exactly the same amount of momentum. But energy must also be conserved in the collision. One of the ways that this can be done is by an increase in the mass of one of the particles. In effect, you have made an energy injection into a particle, which increases its mass several hundredfold without actually changing its character."

Immediately, the energy-bloated particle decays into a pandemonium of different particles. Physicists are able to locate these collision aftermaths by tracing the pathway of the drift-chamber particle. In the Rockefeller experiments, studying the particles produced by this process of diffractive excitation, the team will be probing the content of the "Pomeron," a particle postulated to play a key role in all small angle collisions. Or, with a little luck, they could discover evidence of the elusive "top" quark, the sixth and final member of the quark family of particles critical to the acceptance of the Standard Model—the overarching hypothesis describing the fundamental components of all matter in the universe. What else might they find? Dr. Goulianos turns his palms up to the sky. "Who knows? This field is as open as the Illinois prairie."

To measure the energy and trajectory of the maverick proton, the drift chamber is filled with a mixture of argon and ethane gas. At the entrance to and exit from the chamber, the proton passes through scintillation counters and releases light, which is converted in the photomultipliers into electrical pulses that start a kind of stopwatch. Almost simultaneously, in the gas-filled detector, the proton bumps into argon atoms knocking electrons out of their orbits. The free electrons then "drift" to four high-voltage wires (at the speed of 50 millimeters per millionth of a second!) located at the top of the chamber. As they approach the wires, attracted by their strong electrical charge, the electrons crash into other argon atoms releasing more electrons, which, in turn, crash into still other atoms, creating an electron avalanche. "The important thing," says Dr. Goulianos, "is to shape the electric field of the chamber so that the electrons move toward the wire with constant speed. When they strike the wire, an electric pulse is created and amplified, stopping the clock."

The time it takes the electrons to travel through the drift chamber can be converted into distance. By comparing information with other beam-line drift chambers, physicists can reconstruct the particle's trajectory to determine its momentum and trace its origin to a collision vertex. Now they can look for the newly energized proton to see if it has decayed into "interesting" particles.

According to Dr. Goulianos, "The questions we are asking are: How is this kind of matter different from ordinary matter? What is the number and nature of particles that it makes per

unit mass? What is the distribution of their momenta? All this is of interest to us because we are making matter in a different way."

"A TOUGH ART"

Since there is a high degree of interdependence among the various teams working on the CDF, and between those of the CDF and the Tevatron accelerator, the Rockefeller physicists inevitably get involved in projects extending beyond their own drift-chamber experiments. Dr. White, for example, who helped build and test the Rockefeller particle detectors, was also called upon to serve with the computer software group as a trouble-shooter, or "godfather," contributing his perspective as a nonspecialist in the field. Another aspect of his work at CDF has been the construction of the section of pipe through which the beam will travel at the B-zero location.

As a boy, interested in fashioning his homemade experiments, he picked up oddities of wire and coil during frequent strolls down Canal Street in New York. Today, the selection process for the beam pipe material and construction is considerably more sophisticated. To maintain ultra-high vacuum the pipe had to have reliable seams and a good surface finish. Also, the pipe had to be extremely thin, since the material between the detectors and the interaction region had to be minimized, yet rigid enough to prevent collapse from atmospheric pressure. A very high vacuum inside the pipe was important lest extraneous molecules deflect the rotating protons and antiprotons from their collision course.

"Ultra-high vacuum is a tough art," says Dr. White, having survived a year-long education in beam pipe manufacture. After scores of materials were considered, the final choice was beryllium brazed with aluminum. Several companies attempted the arduous and finicky process of folding the beryllium into a cylinder and welding it with aluminum to form a seamless, vacuum-tight pipe. After limited success by a Japanese company, Dr. White feared that the pipe would not be ready in time for the CDF run. So, with six months remaining, he turned the project over to a San Francisco-based company. "Eventually," he says of the $100,000 pipe, "we learned how to make the thing."

WHY PARTICLE PHYSICS?

Drs. Goulianos and White are dining at Fermilab's unofficial faculty club, named *Chez Leon* in honor of Fermilab Director Leon Lederman by Nancie Bég, wife of Rockefeller physicist M.A.B. Bég, on an early visit to the laboratory.

"Did you see the smoke?" asks Dr. White, referring to the "prairie burn" held that morning. Twice a year, conservationists from the Nature Conservancy torch 660 acres of prairie inside the Tevatron's main ring, hoping that successive generations of indigenous prairie grass will eventually rout out its imported Eurasian competitor. After the burn, one of the conservationists had remarked that while it will take years to restore the prairie, millions were being spent on experiments in the Tevatron that last a millisecond and do little to improve the quality of life.

Both physicists at the table are used to countering arguments that physics is a luxury. Dr. Goulianos comments that the same might have been said about the study of electricity a hundred years ago. He also points out that lasers for surgery, CAT scans, and machines for medical imaging all have their origins in basic physics research. Finally, the answer to the question, Why particle physics?—or, Why any basic research?—can be found in the deep-seated human need to construct a logical and succinct description of the physical world. The intellectual heritage of particle physics can be traced back to the beginnings of science. In a sense, the road to Fermilab began twenty-five hundred years ago on the Greek colony of Miletus when Leucippus and his pupil Democritus first speculated on "atoma," the fundamental building blocks of matter. With instruments and techniques undreamed of by their Greek predecessors, physicists like Drs. Goulianos and White continue to ask the deceptively simple question, What is matter made of?—and perform experiments that provide a piece of the answer.

Dinner is over and the two scientists excuse themselves from the table. A few more hours work await them before turning in. Nightfall shrouds the landscape and their footsteps on the gravel driveway punctuate the stillness. In the distance, the lights of Wilson Hall can be seen above the Midwestern praire like a beacon. □

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