NOBEL PHYSICS PRIZE TO CHARPAK FOR INVENTING PARTICLE DETECTORS

Georges Charpak

The 1992 Nobel Prize in Physics has gone to a virtuoso instrument maker. The Royal Swedish Academy of Sciences awarded the prize to Georges Charpak of France "for his invention and development of particle detectors, in particular the multiwire proportional chamber."

He began by building nuclear physics detectors as a graduate student in Frédéric Joliot's Paris laboratory in the early 1950s. Nowadays in nominal retirement from CERN, the European high-energy physics laboratory near Geneva, he designs detectors primarily for biomedical uses. But Charpak's fame rests securely on the detectors he pioneered for high-energy physics. The multiwire proportional chamber and its progeny—the drift chamber and the time projection chamber—have for two decades now been the principal means by which high-energy physicists visualize the tracks of the particles emerging from collisions at the big accelerators.

It was quite different 30 years ago. "In those days the bubble chamber was the king of the accelerator floor," recalls Charpak. Bubble chambers produced beautiful pictures with superb spatial resolution. But they had two serious limitations: They couldn't be triggered on promising events, and their output was in the form of photographs. The only way to find interesting collisions was to look through thousands of pictures by eye. And the bubble chamber's thermodynamic expansion cycle limited its repetition rate to about one picture a second. That was a tolerable state of affairs in the early days of high-energy physics, when almost every scattering event was of some interest. But as experimenters began to concentrate on rarer phenomena, the limitations of the bubble chamber became increasingly onerous.

In 1958 Shuji Fukui and S. Miyamoto in Japan built the first successful spark chamber. "That was a big step forward," Charpak told us. Spark chambers had a microsecond of memory before the ionization created by a traversing track was dissipated beyond recall. That was enough time for a logic circuit to decide, on the basis of signals from scintillation counters, whether an event was interesting enough to record.

But the early spark chambers also had to rely on photographic recording. They were, in essence, stacks of metal plates separated by gas-filled spaces. A traversing charged particle left behind a trail of ionized gas molecules. If the scintillation counters indicated that a worthwhile collision had occurred, a high-voltage pulse would be applied to the plates, causing sparks to jump across the gaps just where the ionization had been. Cameras looking at the gaps between the plates would thus a record pattern of sparks that gave a reasonable facsimile of the particle trajectories. The spatial resolution wasn't very good, but the chamber needed only a few milliseconds to recover from a voltage pulse. That gave it a repetition rate hundreds of times faster than a bubble chamber's.

This very speed at accumulating pictures exacerbated the problem posed by photographic data taking. "It meant 10 million more pictures a year for the already overworked high-energy community and its army of scanners to analyse," Charpak explained. "A horrible prospect, and it imposed an absolute upper limit on high-energy experiments. You simply can't look at a billion pictures a year." So like many others in the early 1960s, he began thinking about about how one might make a filmless spark chamber.

Coming to CERN

Charpak had been at CERN since 1958. Leon Lederman, on sabbatical leave from Columbia University, had recruited him to CERN to participate in a measurement of the anomalous magnetic moment of the muon. Lederman had been impressed a year earlier when he heard the young man give a talk in Padua about his attempts to exploit sparking devices for particle detection. "That's all well and good, Georges," Lederman recalls telling Charpak. "But now let's go do some real physics. Come and help me measure $g-2$ for the muon."

"So he reluctantly put that detector stuff aside and joined our experiment," Lederman recounts. "But one day a few months later he came storming in, waving these beautiful spark chamber pictures Fukui had just published. From then on he always blamed me for having stopped him from inventing the spark chamber." Charpak confirms the story. "But of course it was in jest," he assures us.

After the $g-2$ experiment, Charpak turned his attention to the problem of filmless spark chamber readout. "I invented two methods," Charpak told us, "but other people found better ways." By the mid-1960s acoustic and wire spark chambers were the favorites. The former used microphones to locate sparks much as one would locate a lightning bolt by noting the times at which several listeners hear the thunder clap. The latter scheme replaced the spark chamber plates with planes of wires. It was then easy to record the very large voltage pulses in the wires near the spark discharge.

But the very violence of the high-voltage discharges that make the sparks so easy to record without amplifiers imposes certain limitations on all spark chambers, with or without film. The discharges do not localize the ionizing trajectory very well, and the spark chamber takes at least a millisecond to recover. That's why Charpak and others began thinking about the next step: operating a multiwire chamber in the much gentler "proportional mode."

Single-wire proportional chambers had been around so long that they were considered quite obsolete by the high-energy community, but not by nuclear physicists. Ernest Rutherford and Hans Geiger had built the prototype in 1908. Their chamber was simply a metal cylinder containing an ionizing gas and a single anode wire running along the axis. If an ionizing particle traverses the chamber, the consequences depend on the potential difference applied between the anode and the cylinder. If the voltage is sufficient to accelerate the initially liberated electrons to energies high enough to ionize other gas molecules, one gets an avalanche of secondary electrons collected at the anode wire. If the voltage is, at the same time, not too high, this anode signal is proportional to the initial ionization, with a multiplication of about 10^4 electrons for every electron freed by the traversing particle. This voltage regime is called the proportional mode.

If one jacks up the voltage for the sake of getting a bigger signal that's easier to detect, one eventually gets to the breakdown, or "Geiger," mode, where the avalanche fully discharges the potential difference. The resulting signal is so big that one needs only a microphone and speaker to hear the familiar click of the Geiger counter. But operating a multiwire chamber in the Geiger mode offers no prospect of spatial resolution or repetition rates much better than one can get with a spark chamber.

Multiwire proportional chambers

Early in 1968 Charpak and his technician Roger Bouclier, whom Charpak describes as having "golden hands," built the first multiwire tracking chamber that operated successfully in the proportional mode. "It was only 10×10 cm," Charpak recalls, "but it worked like a charm from the beginning." Charpak thinks that he succeeded where others had failed because of his nuclear physics background. "I had built single-wire proportional chambers for my thesis experiment in Joliot's lab. I really understood the electrostatics of proportional chambers. None of these high-energy physicists had ever seen one. They were trying to make low-voltage versions of wire spark chambers, and that doesn't work."

In Charpak's early multiwire proportional chambers a parallel array of fine, grounded anode wires was sandwiched between two cathode plates or meshes at several kilovolts dc in an atmosphere of ionizing gas. (See the figure on page **19**.) Each 25-micron-thick anode wire had to have its own little amplifier, because signal pulses are quite weak in the proportional mode. The gap between anode and cathode planes was about 6 mm, but the spacing between adjacent anode wires was only about 2 mm. And it was this very small anode wire spacing that determined the spatial resolution of the instrument. "People had been afraid to put sensing wires so close together because they thought that capacitative coupling would spoil their independence," Charpak told us.

"But in reality you find something quite miraculous," he said, "even with the wires only a millimeter apart." Testing his first little chamber with an x-ray source, Charpak found that the one anode wire closest to a traversing ionizing particle gave the negative voltage pulse one would expect. But the two anode wires on either side of it unexpectedly exhibited *positive* pulses. "When I saw that, I knew I had a practical detector." The negative pulse flanked by two induced positive pulses identified the wire of closest approach quite unambiguously. And furthermore, it soon became clear that the same mechanism that was inducing the positive pulses could turn a single planar wire chamber into a two-dimensional detector.

Electrons liberated by an ionizing particle drift toward the nearest anode wire. But the avalanche doesn't begin until they are within about 50 microns of the wire, because that's where the electric field lines start to converge to produce a strong accelerating field. It's all the positive ions created in the avalanche, rather than the electrons, that produce most of the negative voltage pulse on the avalanche wire, essentially because the ions traverse a much larger potential difference as they move far away from the wire than does the infalling avalanche of electrons. Charpak quickly understood that the recession of the ions was also responsible for inducing the positive pulses on the adjacent wires.

Charpak and his colleagues soon found that the motion of the ions induced positive pulses at the cathode planes as well. They demonstrated that one could exploit these induced pulses to locate the avalanche in two dimensions by segmenting one of the cathode planes into strips running perpendicular to the anode wires. The induced cathode pulses are essentially simultaneous with the anode pulses; they appear long before the lumbering ions actually reach the cathodes. The anode and cathode pulses are recorded within about 20 *nano*seconds of the ionizing particle's passage. That determines the time resolution of the instrument.

The Charpak chamber's maximum repetition rate is determined by the time it takes a wire to recover from an avalanche. In a proportional chamber, unlike a spark chamber, the voltage between anode and cathode is low enough to be kept on continuously. The chamber does not have to be pulsed in response to an external trigger. Nor is this dc voltage discharged by the avalanche. Therefore a wire is fully ready to resume its vigilance within a few microseconds of having recorded the passage of a particle. So a multiwire proportional chamber can look at a million events per second. Of course one doesn't want to store all those events. The readout from the wires is fed directly to an on-line computer that decides which events are worth a second look. That could be as few as one collision in a million.

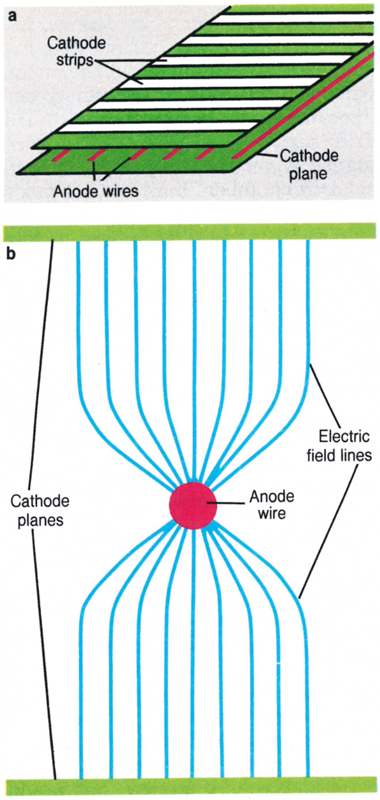
To follow the trajectories of high-energy charged particles in three dimensions one simply stacks wire chambers with their anode wires running in orthogonal directions. The energy lost in traversing a single chamber is negligible. Therefore there's no need to bother with segmented cathodes. The cathode pulses become important when one is looking at low-energy or neutral particles that can't get through more than one chamber. A single Charpak chamber with a segmented cathode can, for example, record a two-dimensional x-ray diffraction pattern.

In 1970 Fabio Sauli joined Charpak's group. He was to play an important role in demonstrating how one could use the induced cathode pulses to get extremely good localization in the direction along the anode wires. Sauli took over the direction of the group upon Charpak's nominal retirement in 1990.

Drift chambers

From the very beginning Charpak noted that the spacing between anode wires need not be the limit of spatial resolution in the direction perpendicular to the wires, *if* one also measured the time delay between the particle's passage (as recorded by external scintillation counters) and the arrival of the avalanche at the wire. This observation spawned the drift chamber, the multiwire proportional chamber's flourishing firstborn. By 1969 Charpak and his colleagues had demonstrated drift chambers with spatial resolutions of 0.2 mm. Recent drift chambers do ten times better.

In a drift chamber the electrons liberated by an ionizing particle typically drift for about 10 cm in a low-intensity electric field before they reach the nearest anode wire. Drift velocities are on the order of 40 microns per nanosecond. The gas and field configuration are carefully chosen to insure uniform drift velocity.



Multiwire proportional chamber, shown in **a**, is a plane of very thin anode wires in ionizing gas sandwiched between cathode planes that are sometimes segmented into strips. The anode wires, held at a dc potential several kV above the cathodes, are typically 25 μm thick, and the space between wires is about 2 mm. The space between anode and cathode planes is typically 3 or 4 times the interwire spacing. Ionized electrons avalanche in the high-field local regions where the field lines converge on the individual wires, as shown in **b**.

This arrangement not only provides superb spatial resolution; it also saves lots of money. Nowadays a typical particle detector system at one of the giant accelerators is four or five stories high. Drift chambers can cover great areas with far fewer wires than one would need with ordinary multiwire chambers. And it's not just wires: Remember that every wire has to have its own little amplifier.

The time projection chamber, first proposed by David Nygren at the Lawrence Berkeley Lab in 1974, is a kind of drift chamber carried to extremes. A TPC is a large gas-filled cylinder that reconstructs ionizing tracks in three dimensions by recording the arrival times of electrons that have drifted as far as a meter to reach a two-dimensional array of anode wires and orthogonal cathode strips at the end cap. This is one case where the induced cathode pulses *are* important in a wire chamber doing high-energy physics. The density of ionization per unit path length is also recorded, as a measure of the particle's velocity.

One does pay a price for large drift lengths. Having to wait for the avalanches makes it difficult to use such chambers in high-intensity hadron colliders like the Superconducting Super Collider or the Large Hadron Collider that CERN is proposing to build.

Doing physics

Charpak's wire chambers caught on very quickly in the early 1970s. They could handle a million events a second without an external trigger, "and they were convenient to build," recalls Lederman. "Any dope could follow Charpak's recipe and build a successful chamber of any size." Charpak demurs: "I am full of admiration for those who built the large wire chambers they're using now. They've solved so many problems with great innovation and skill."

Jack Steinberger at CERN was one of the first to exploit Charpak's invention. In 1970 Steinberger's group used multiwire proportional chambers at the Proton Synchrotron to study *CP* violation in the decay of neutral K mesons. A year later, the first really big Charpak chamber (70 000 wires) was installed at the Intersecting Storage Rings, CERN's new proton–proton collider. Wire chambers were an essential part of the spectrometer system with which Samuel Ting's group discovered the J/ψ meson, the first manifestation of charmed quarks, at the Brookhaven Alternating Gradient Synchrotron in 1974. Ting shared the 1976 Nobel Prize with Burton Richter, whose group at SLAC discovered the J/ψ at just about the same time. Ting's was the first Nobel Prize experiment to use Charpak chambers, but it wasn't the last: Wire chambers were at the heart of the 2000-ton detector with which Carlo Rubbia's group found the Z^0 and $W^\pm$, the superheavy bosons that mediate the weak interactions, in 1983 at CERN's recently completed SPS proton–antiproton collider.

In the late 1970s Charpak began looking for new ways to track particles. He is particularly proud of the multistage avalanche chamber, which he designed in the early 1980s in an attempt to surpass the repetition rate limits of wire chambers. This multistage chamber uses parallel plates in place of wire planes. "It's such a good detector that, if I had invented it ten years earlier, wire chambers would be dead by now," Charpak asserts. Nonetheless the multistage avalanche chambers haven't as yet seen much use in experiments. "There's so much inertia in high-energy physics," explains Charpak. "If you've spent five years building a detector, and someone comes along with something better, you don't listen—because you can't."

Biomedical imaging

In recent years Charpak has given his attention almost entirely to devising detectors for use in biology and medicine. Much of this work is still done at CERN, but Charpak has also undertaken entrepreneurial ventures that supply detectors to hospitals and biological laboratories.

"The pioneering work on x rays with wire chambers was done by Victor Perez Mendez at Berkeley," Charpak told us. In the early 1970s Perez Mendez began using multiwire proportional chambers to do x-ray imaging with synchrotron radiation. "I started to get interested in biology in 1974,"recalls Charpak,"when [Rudolf] Mössbauer told me there was a real need for better x-ray detectors."

In a multiwire x-ray imaging chamber the avalanches at the anode wires are initiated by photoelectrons liberated by the x rays in a gas-filled drift region that precedes the wire plane. A very sophisticated "spherical drift chamber" built by Charpak's group in 1984 is still in constant use by protein crystallographers at the Orsay synchrotron light source.

Charpak has also developed imaging chambers for biological radiography with beta-emitting isotopes. The traditional method was simply to press the isotope-labeled sample up against a piece of photographic film. The result, Charpak contends, "was very ugly pictures that required high radioisotope levels and very long exposure times. I always thought you could replace film with detectors, just as we did in high-energy physics."

Charpak's beta-imaging detectors, one of which is in routine use at a Geneva hospital, do indeed exploit several ideas he developed first for high-energy physics in the 1980s. They are essentially parallel-plate multistage chambers whose avalanches generate light pulses imaged by CCD arrays. "In one afternoon you get a picture of a quality that would take three months with film," Charpak told us. "Last spring I made one for the Institut Pasteur. After ten days they had a publishable paper."

Prisoners west and east

Charpak was born in Poland in 1924. The family emigrated to France when Georges was 7 years old. Having just turned 19 in the wartime summer of 1943, Charpak was jailed by the Vichy authorities in southern France as a "terrorist." After a year in prison he was deported by the Nazis to the concentration camp at Dachau, where he remained until the camp was liberated in April 1945. "Luckily I was only regarded as a Pole and a terrorist," Charpak told us. "They didn't know that I was a Jew."

Charpak became a French citizen in 1946. Two years later, with a civil engineering degree from the École des Mines in Paris, he went on to become Joliot's graduate student in nuclear physics at the Collège de France.

For many years Charpak has been a committed and visible champion of the cause of scientists imprisoned by despotic regimes. He was a founder and leader of the CERN chapter of the SOS committee for Soviet dissidents Andrei Sakharov, Yuri Orlov and Anatoly Sharansky. Charpak knows better than most what it means to be deprived of freedom.

—BERTRAM SCHWARZSCHILD

MARCUS WINS NOBEL PRIZE IN CHEMISTRY FOR ELECTRON TRANSFER THEORY

Rudolf Marcus of Caltech was at a meeting of the Electrochemical Society in Toronto when he learned that the Royal Swedish Academy of Sciences had awarded him the 1992 Nobel Prize in Chemistry "for his contributions to the theory of electron transfer reactions in chemical systems." The meeting participants were only too glad to raise their glasses to Marcus, for the fundamental theory he elucidated in the 1950s and 1960s underlies much of their work. Its applications include such diverse phenomena as photosynthesis, electrically conducting polymers, chemiluminescence and corrosion. As Marcus remarked to us, "the field continues to grow and grow."

Out of a simple question...

Marcus told us that he was led to consider the problem of electron transfers between molecules when he was a young associate professor at the Polytechnic Institute of Brooklyn in 1955. At that time Marcus had already read 11 books and published two papers on electrolytes, his interest in the subject having been stimulated by a question posed by a student in his class. Hence he was well prepared to critique some work by Willard Libby concerning the transfer of an electron between molecules in solution. Marcus was intrigued by Libby's approach but bothered by some aspects that didn't seem quite right. He tried his hand at the problem and added a key factor neglected by Libby: the role played by fluctuations in the dielectric polarization. Marcus published this work[1] in 1956, in the first of a series of papers that he wrote over a nine-year period developing what is now called the Marcus theory.

This theory focused on the transfer of electrons between two molecules that interact only loosely during the transfer, so that no bonds are formed or broken. One of the simplest such reactions is a "self-exchange" reaction in which an electron is transferred from one ion to another ion of the same element that is in a different valence state. For example, in the following reaction, an electron is transferred from the ferrous ion, whose valence is $+2$, to the ferric ion (denoted by an asterisk), whose valence is $+3$:

$$Fe^{2+} + Fe^{*3+} \rightarrow Fe^{3+} + Fe^{*2+}$$

Although this reaction is about the simplest one could imagine, its rate depends on a very large number of variables: the positions of the nuclei, their vibrational state, the type of solvent, the orientations of polarized solvent molecules, the temperature and so on. There are also thousands of spatial coordinates. The potential energy surfaces of the reactants and the products must be drawn in an N-dimensional space, where N is the number of coordinates.

Marcus collapsed all these coordinates to one composite "nuclear coordinate," which represents essentially the state of the entire system, so that the free energy could be plotted against just one variable rather than as a multi-dimensional surface. Mar-