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Wolfgang K. H. Panofsky

Scientist and Arms Control Expert

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Abstract

Wolfgang K. H. Panofsky is remembered as the legendary founder and first director of SLAC, the Stanford Linear Accelerator Center. He devoted his life to teaching and research in accelerator and particle physics, to science policy, and to his work as a science advisor to both the U.S. and foreign governments, and to world peace, as an expert on arms control and international security. He was admired by all who had a chance to meet and interact with him, and who simply called him Pief.

CONTENTS

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1 The Early Years, 1919 - 1945

Wolfgang K. H. Panofsky was born in Berlin (Germany) in 1919. His father Erwin became one of the most eminent art historians of his time, specializing in Renaissance paintings and iconology. His mother Dorothea was the daughter of Albert Mosse, a famous jurist and member of a family who owned a publishing house and a daily newspaper in Berlin (1).

In 1920, Erwin Panofsky accepted a faculty position at the University of Hamburg, and the family lived there until they emigrated to the United States in 1934. From the age of ten, Wolfgang and his one-year older brother Hans attended the Johanneum, a classical gymnasium founded more than 400 years earlier. The education was classical indeed, Latin and ancient Greek were taught throughout, but there were no classes in modern languages or science, except for the last two years prior to graduation. The two boys spent much of their free time assembling innovative gadgets with their Märklin erector and train sets. Their parents referred to them as "unsere beiden Klempner" (German: "out two plumbers"), which revealed the not uncommon attitude of the German academics, educated in the humanities, towards those engaged in science and engineering.

In 1933 Erwin Panofsky was dismissed from his position at the university. Having spent a sabbatical at New York University (NYU) the year before, he accepted a dual teaching position at NYU and Princeton. The following year he was elected to join the Institute for Advanced Study, as its first member from the School of Humanities. Albert Einstein and Wolfgang Pauli were among the family's emigrant friends. Wolfgang and Hans (nicknamed Piefke and Paffke, slightly derogatory names derived from German cartoons (2)) were admitted to Princeton at the age of 15 and 16. They enrolled primarily in technical courses and Latin, given their very limited knowledge of English. The boys graduated with highest honors, and Wolfgang, as salutatorian of his class, presented the graduation speech in Latin.

Accepting a personal invitation by Robert A. Millikan, then president of Caltech, Wolfgang Panofsky, entered Caltech in 1938. He took courses from W. Smythe (electromagnetism), F. Zwicky (classical mechanics), R. A. Millikan (atomic physics), L. Pauling (quantum mechanics), R. Tolman (statistical mechanics), and C. C. Lauritsen (nuclear physics). His thesis advisor was Jesse DuMond whose research was centered on high-powered x-ray tubes. The assigned thesis topic was "Measurements of the endpoint of the x-ray spectrum produced from the bombardment of electrons of 20 keV to determine h/e, the ratio of the Planck constant to the charge of the electron" (3, 4). Since research funding was limited, most of the equipment was designed and built in Caltech's shops by Professor DuMond and his students. So Panofsky gained first-hand experience in mechanical and electronics design and shop work.

The year 1942 was a special one for the young Panofsky. He received his PhD, became a U.S. citizen, and was given a national defense appointment as associate physicist. The same year, he married Adele DuMond, his advisor's eldest daughter. The following year, twins were born, the first two of five children.

His first war-related project was the development of a firing-error indicator for target practice of anti-aircraft bullets (5). He designed a device which consisted of a pair of condenser microphones that would frequency-modulate an oscillator and determine the miss distance. After extensive field tests, the device was manufactured commercially and widely applied at military test sites.

In 1944, Luis W. Alvarez realized that the measurements of ultrasonic shock waves might also be used to determine the power of nuclear explosions. Thus he engaged Panofsky as a consultant to the Manhattan Project to develop such a device. When on August 6th, 1945 the atomic bomb was detonated over Hiroshima (and the second one was dropped three days later over Nagasaki), the calibrated shock-wave detector was released on a parachute from the bomber and its radio-transmitted signal was recorded from a nearby aircraft observing the explosion. Its energy release was measured to be 13 kt of TNT equivalent. The device survived the explosion and is on display at the Hiroshima Peace Museum.

2 Research at UC Berkeley's Radiation Laboratory, 1945 - 1951

After the end of the war, Alvarez convinced Panofsky to join the staff of the UC Radiation Laboratory (UCRL) and to work with him on the construction of a 32 MeV proton linear accelerator. This was Panofsky's first experience with accelerators. He focused primarily on detailed beam-dynamics calculations and the design of radio-frequency (RF) cavities (6). The design of this linac (7) became the basis for future accelerators of increasing energy and intensity. Another much more ambitious project was MTA (Materials Testing Accelerator), that was to be used as a very intense neutron source for the production of tritium for nuclear weapons. Panofsky contributed to many aspects of the cavity design and beam orbit calculations. Because of the weak focusing by solenoids, the RF cavity had a diameter of 20 m and the energy stored in the huge electromagnetic cavity was so large that any discharge would be highly destructive to the copper enclosures. Nevertheless, the prototype operated at peak currents of up to 0.22 A with a 20% duty cycle. The project was abandoned in 1951 when other fissionable materials became available.

Panofsky's first particle physics experiments focused on proton-proton scattering at 32 MeV. The resulting differential cross section (8) showed no evidence for P and D wave contributions which had been expected at these energies. In the following years, Panofsky engaged in a number of seminal experiments at the 185-inch cyclotron to study π^- absorption at rest (9), which yielded very valuable information on the properties of π mesons. Together with two graduate students, he devised a high-pressure hydrogen target, followed by a well shielded pair-spectrometer to detect photons produced in the interaction $\pi^- p \rightarrow n\gamma$, and to measure the π^- mass (Figure 2a). In a follow-up experiment with improved photon detection, the group was able to confirm the existence of the neutral pion in the process $\pi^- p \rightarrow n\pi^0$, by detecting the decay $\pi^0 \rightarrow \gamma\gamma$ (9) (Figure 2b). The experiment also resulted in measurements of the masses of the neutral and charged pions with an accuracy of close to 1%. As a sequel, the group studied π^- interactions in deuterium and observed the process $\pi^- d \rightarrow nn\gamma$, but found no evidence for $\pi^- d \rightarrow nn\pi^0$ (Figure 2c). This feature suggested that the π^- and π^0 had the same parity. The inferred rate for $\pi^- d \rightarrow nn$ relative to $\pi^- d \rightarrow nn\gamma$ led to the conclusion that the most likely spin-parity assignment for the π^- was $J^P = 0^-$.

Soon thereafter, Panofsky joined Jack Steinberger to work on a photo-production experiment at the 300-MeV electron synchrotron. A coincidence of two photons from the interaction $\gamma Be \rightarrow X\gamma\gamma$ resulted in a very clean sample of events and a precision measurement of the π^0 mass. It also confirmed the $J^P = 0^-$ assignment of the π^0 meson (10).

During these first five years at UCRL, Panofsky supervised 14 graduate students, and in parallel had extensive teaching responsibilities, at graduate and undergraduate level. He devoted special attention to a graduate course on electricity and magnetism, in which he emphasized the evolution of Maxwell's equations from fundamental underlying physics concepts, rather than from theoretical derivations. Since he could not find any suitable textbook written in English, he developed his own mimeographed lecture notes, which underwent continuous updates and corrections by students and colleagues. He accidentally found a co-author in Melba Phillips of Washington University. By mail correspondence they wrote a text book that is still in use today (11).

After only six months at UCRL, Panofsky was appointed to an assistant professor position at UC Berkeley. Two years later, he was promoted to associate professor with tenure. Alvarez summarized his assessment of his junior colleague in his letter of recommendation (12). "I think it is no exaggeration to say that Panofsky is an amazing person. He has the most thorough grasp of basic physics I have ever seen in a man of his years. He works quite difficult theoretical problems with no apparent effort. At the same time, he is completely at home in the laboratory, and is one of the best practical radio engineers I know. He had no contact with microwave radio during the war, but he is now giving a lecture course on the theoretical and practical aspects of the field. I am with him a good part of each day, and I haven't the slightest idea where he finds the time to learn what he teaches."

Panofsky appreciated the unique and diverse opportunities at UCRL and envisaged a productive career at Berkeley. Unfortunately, this was not to be the case. In early 1950, concern about the infiltration by communist spies led to the decision by the UC Board of Regents to augment the commonly administered loyalty oath on the U.S. constitution by an affirmation that a staff or faculty member was not affiliated with the Communist Party (13). To many researchers, who were used to security clearance formalities, this was just another intrusion into their personal lives, imposed by the U.S. and California governments. Most of them, including Panofsky, signed the oath, even though they disapproved of the measure. Others, especially European emigrants who had suffered under fascist regimes, objected strongly. Nevertheless, the Regents voted to terminate more than 150 employees who refused to sign the oath, among them physicists Giancarlo Wick and Geoffrey Chew. At this point, Panofsky informed his superiors that he intended to leave Berkeley. This decision was much to the relief of his parents, who had followed the developments from Princeton in great despair. Panofsky turned down offers from Columbia, Princeton and Harvard, and chose to stay in California and to accept a full professorship at Stanford. Alvarez tried to dissuade him from leaving, warning him, "Oh Pief, you'll fade away at Stanford. Nothing goes on there, you'll never be able to do any significant research (12)."

3 Early Years at Stanford, 1951-1963

In the post-war years, Stanford University had embarked on a major expansion of its science and engineering departments by attracting world-class scientists and engineers to join its faculty. The prewar invention of the klystron by Russell H. Varian, Sigurd F. Varian, and William W. Hansen was the basis for the electron accelerator development at Stanford. It was also the critical component of radar, telecommunication, and other microwave applications.

At that time, Panofsky did not know much about Stanford, but he was very interested in the Mark III, an electron linear accelerator with a maximum beam energy of 1 GeV, proposed by Hansen. This was the third in a series of linear accelerators at Stanford, and it benefitted from the invention of the high-power klystron, advances in vacuum technology, and from operational experience with its smaller predecessor, the Mark II. Still, there were innumerable problems waiting to be solved. Panofsky teamed-up with Edward Ginzton, a Stanford professor and expert on microwaves, and became involved in all aspects of the design, fabrications, assembly, and tests. Beyond that, he took on the task to design and build a hall for two detectors, a spectrometer which Hofstadter had proposed for mesurements of elastic e^-p scattering and a second for a variety of experiments he was planning.

Among the measurements performed at the Mark III accelerator, the best known was the study of nucleon structure by the group led by Hofstadter (14,15), who was awarded the Nobel Prize in 1961. These measurements were interpreted in terms of a proton having a smooth charge distribution with a radius of $(0.77 \pm 0.10) \times 10^{-13}$ cm.

Panofsky's group of mostly graduate students started a series of landmark experiments, performing precision measurements of e^-p cross sections, of the electro-production of pions and of baryon resonance formation. He designed and built a double-focusing, zero-dispersion spectrometer (16) to measure inelastic electron scattering. This was a forerunner of the large spectrometers that were built at the Stanford Linear Accelerator Center (SLAC) years later. The spectrometer had large dispersion between two magnets where slits were inserted to define the energy of the scattered electrons that were refocused by the second magnet. In this way, the backgrounds were effectively suppressed and detectors of modest size were adequate to detect the scattered electrons. Another experiment led to the first observation of electro-production of muon pairs and measurements of the Michel parameter in muon decay (17). Much of this research was of great interest to theorists, among them Leonard Schiff and Sidney Drell who assisted with predictions and the interpretation of experimental results.

It had become evident that precision tests of quantum electrodynamics (QED) required processes with large momentum transfer which could not be reached with electrons striking a stationary target. In 1958, Gerald K. O'Neill of Princeton University teamed up with Panofsky and three young research associates, W. Carl Barber, Burton Richter and Bernard Gittelman, and proposed to use the Mark III as an injector for a pair of figure 8-shaped electron storage rings with a common section to enable e^-e^- collisions at 1 GeV center-of-mass energy (18). This experiment was not only extremely challenging for two small university groups, it required large funds which Panofsky was able to raise from the Office of Naval Research. It took five years to complete the two rings, each 3.5 m in diameter. Much of what we know today about storage rings was learned at this pioneering machine: for instance, beam resonance formation, beam-beam interactions, synchrotron radiation, and desorption of gas from metal walls of the vacuum pipes. These storage rings still hold the record for a single-bunch current of 600 mA. The measurements proved the validity of QED (19) to distances of close to 10^{-15} cm and placed stringent limits on lepton number conservation. Richter realized that e^+e^- annihilation rather than e^-e^- scattering would enable studies of hitherto unobserved processes. The realization of this idea, the construction of the storage ring SPEAR (20), would have to wait another decade.

During his first years at Stanford working on the Mark III accelerator, Panofsky attracted a number of excellent students and young scientists, engineers, and technicians, some of whom had served in World War II. Given the success of the operation of Mark III and its highly rated physics research program, Panofsky, Ginzton and others began to develop a conceptual design for the next generation, multi-GeV accelerator. The physics goals were to a large degree extrapolations of the experimental program at Stanford: nuclear form factors and tests of QED, electro-production of hadrons and resonance formation, and studies of particle properties with secondary beams.

The technical design was mostly based on experience with Mark III, but required major extrapolations:

- the accelerator was to be built in 30 section of 100-m length, each equipped with its own power substations, vacuum system, sub-boosters, powered by eight 24-MW klystrons;
- the electron bunches were to be accelerated to energies of up to 20 GeV by an alternating axial electric field with a frequency of 2,856 MHz inside a cylindrical, disc-loaded copper structure;
- two experimental areas were to share the beams: Endstation A with three spectrometers to measure $e^{\pm}p$ and $e^{\pm}n$ scattering, initially with unpolarized beams and unpolarized or polarized targets, and Endstation B for experimentation with secondary beams of photons, pions, or kaons.

Ginzton took charge of the accelerator R&D. Together with Richard Neal he built a 25-m long accelerator, referred to as Mark IV, to serve as a testbed for critical components. The building and testing of the Mark IV, located on the Stanford Campus, was subsidized by General Electric, in return for access to details of the design and test results. The Mark IV beams were also used for treatment of cancer patients, a technology that subsequently spawned a multi-billion dollar industry, with General Electric and Varian Associates in Palo Alto as the leading suppliers worldwide.

In 1957, a 64-page proposal was submitted. The White House designated the Atomic Energy Commission (AEC) as the agency responsible for this new national high-energy physics facility. The estimated construction costs were 114 M$, of which 25% were set aside for escalation and contingency, to cover inflation and unforeseen expenditures. Panofsky realized early on that the full exploitation of the new accelerator would require the construction of large experimental facilities. If experiments were to be ready at the turn-on of the accelerator, they would have to be designed and built in parallel with the accelerator. The estimated cost of the experimental facilities and research equipment was 18 M$. Support for continued research and development and operation of the new facility was to be provided separately.

In the following five years, Panofsky devoted enormous energy and time to secure government approval for the project. He encountered objections from government officials, Congress, and also from members of the scientific community who did not share his pioneering vision of the reach of high-energy electron beams. It took his immense foresight and courage to convince the government of the potential of this very large and costly project. Numerous congressional hearings were held and committees were convened to evaluate the concerns and provide advice. After the project received approval for construction on September 15th, 1961, drawn out negotiations followed concerning the responsibilities of the AEC vis-a-vis Stanford as the contractor and the project leadership at SLAC. This dispute came close to endangering the whole project. It required the support and wise judgment of David Packard and others to resolve the controversy in Panofsky's favor: Stanford retained the full responsibility for all construction activities.

Of the three possible locations for the accelerator and laboratory on Stanford property, the site parallel to Sand Hill Road was chosen. A 50-year lease was signed in April 1962, giving the AEC full use of the 170-ha site for an annual fee of one dollar. The new laboratory was designated to be a national facility operated by Stanford University under contract with the federal government, open to national and international research groups on the basis of proposals.

4 Director of SLAC, 1962-1984

4.1 Building of a National Research Facility

Construction of the linear accelerator started in July 1962 (21). After the untimely deaths of Russel Varian in 1959 and Sigurd Varian in 1961, Ginzton resigned from Stanford University to take over the management of Varian Associates, the first company in the Stanford Industrial Park. Panofsky became director of SLAC by default, apparently without an official letter of appointment from Stanford President J. R. Sterling or the AEC. He held this position until his retirement in 1984. He appointed Richard Neal to oversee and manage the construction of the accelerator.

In spite of his many administrative duties and heavy travel schedule, Panofsky stayed involved in all important technical and scientific matters, during the construction as well as during the many years to follow. Among the many technical challenges were the fabrication of the klystrons and the accelerator structure which was assembled from pre-machined copper disks and rings. Roughly 100,000 brazed joints had to be made with a thin layer of silver between the copper pieces. In almost 50 years of operation, none has leaked! Figure 3 shows the accelerator components, the copper elements of the disc-loaded wave guides, and the waveguide feeding the microwaves generated by the klystrons.

The construction of the accelerator was completed as planned in May 1965 (21). First beams of 10 GeV were delivered six months later, and stable beams became available to experiments in 1967. The construction and instrumentation of the linac were accomplished within the projected budget. Most of the contingency funds were used for the beam distribution and the target areas, which had not been designed in detail at the time of the proposal.

As Panofsky pointed out in his autobiography (1), "the establishment of a new laboratory far transcended the construction of the accelerator complex and its research facilities, it meant creating an environment that would enable great scientists to perform outstanding research". To optimally exploit the unique research potential of SLAC as a single-purpose laboratory, built and operated by Stanford, this facility was to be open to qualified physicists from the U.S. and abroad. To work out policies and procedures for SLAC as a national facility, Panofsky established a Scientific Policy Committee whose membership was approved by the Stanford Board of Trustees and the AEC. The Committee reported to the President of Stanford who shared the findings regarding the operation and the scientific program with the SLAC director and the AEC.

Panofsky appointed a separate Program Advisory Committee (PAC) to advise him on establishing a "vigorous, forward-looking research program in high-energy physics, with scientific priority determining the allocation of machine time" (21). The final selection of experiments and their scheduling remained the responsibility of the SLAC director. As of July 1967, SLAC had received 24 proposals, of which 17 were approved for beam time; about half of them were carried out by collaborations involving Stanford or SLAC scientists.

Panofsky had realized early on that to establish intellectual leadership and to take on an educational role, SLAC needed to recruit its own faculty. In the appointment of faculty members, associate directors, and department heads, he selected persons primarily on the basis of their scientific and technical expertise. Richard Neal and Joseph Ballam served as associate directors for the technical and research division for many years, as did the deputy director Sidney Drell, who also headed the Theory Group.

From the very beginning Panofsky emphasized that the laboratory's success would not solely depend on its management team, but on all of its highly qualified scientific and technical staff who considered their personal achievements as valued contributions to the success of the laboratory as a whole. A sign of this principle was Panofsky's open-door policy: any member of the staff or visitor could drop into his office, an opportunity that was rarely abused. He stayed involved in all aspects of the laboratory and had an innate ability to resolve conflicts and problems constructively. Once operation started, he would routinely drop in at various locations at SLAC, meeting accelerator maintenance crews and operations' staff, as well as scientists overseeing the data taking of the experiments.

4.2 Electron-Nucleon Scattering at SLAC

Panofsky devoted special attention to the design and construction of the experimental areas, in particular Endstation A which housed three spectrometers (Figure 4). They were designed to measure for electron beams of different incident energies E_e, the energy E'_e of the electrons scattered off a nucleon target at angles θ relative to the incoming beam. Later on, experiments with incident positrons and polarized electrons were carried out.

As stated in the initial proposal, SLAC's primary research focused on scattering of electrons on protons and neutrons, extending from elastic to inelastic processes resulting in the excitation of nuclear resonances. From the measured quantities, the four-momentum transfer squared $q^2 = 2E_eE'_e(1 - cos\theta)$, the energy loss of the electron $\nu = E_e - E'_e$, and the invariant or missing mass of the final hadronic system $W^2 = 2M\nu + M^2 - q^2$ can be determined. Here M refers to the mass of the nucleon. The differential rate can be written in terms of the Mott scattering σ_{Mott} and two structure functions, W_1 and W_2, (Figure 5a),

$$\frac{d^2\sigma}{d\theta\, dE'_e}(E_e, E'_e, \theta) = \sigma_{Mott}\left(W_2(\nu, q^2) + 2W_1(\nu, q^2)\tan^2\theta/2\right) \tag{1}$$

While the new measurements of electro-production of resonances confirmed earlier measurements at lower energies, the data showed a slowly varying cross section as a function of q^2 for "deep inelastic" scattering (DIS), i.e., events in which the nucleon fragmented into higher mass states, $W > 2\,\mathrm{GeV}$. The yields (Figure 5b) were $1 - 2$ orders of magnitude larger than expected from 1956 measurements by the Hofstadter group (15).

Several theorists had been speculating what might happen to the proton, when it was struck hard at higher energies, in particular at higher q^2. Among them was a young theorist at SLAC, James Bjorken, who wondered whether history would repeat itself, and these measurements would reveal the structure of the proton, just as Ernest Rutherford had discovered the structure of atoms from large-angle scattering of α particles. Based on current algebra, Bjorken conjectured that if there were hard kernels inside the nucleon, then for large q^2 and large ν the structure functions W_1 and W_2 would become functions of the ratio $M\nu/q^2$, and the rate would be independent of ν and q^2 (23, 24).

The measurements were first presented by Panofsky in 1968 at the International Conference on High Energy Physics in Vienna (25), showing the large data rate for DIS and scaling for $q^2 > 4\,\mathrm{GeV}^2$ and large ν (Figure 5), as predicted by Bjorken. The interpretation of these results remained unclear, primarily because Bjorken's predictions were derived from current algebra sum rules, which most experimenters found difficult to understand. A simpler explanation was given by Richard Feynman at a seminar a month later at SLAC (26). He confirmed Bjorken's predictions of scaling, explaining that the data revealed the momentum distributions of "partons" inside the proton, as shown in Figure 5c. The leading scientists, Richard Taylor, Henry Kendall and Jerome Friedman, were awarded the Nobel Prize for Physics in 1990 for this discovery which established quarks as constituents of nucleons (27–29). There can be no doubt that without Panofsky's vision and realization of the analyzing power of high-energy electron beams this phenomenon would not have been discovered for many years.

Another fundamental discovery was made a decade later following the development of a new type of source for longitudinally polarized electrons by photoemission from a gallium arsenide photocathode illuminated by a circularly polarized laser. A team lad by Charles Y. Prescott proposed an experiment to prove the impact of weak interaction on elastic $e^- d$ scattering. Since the interference of the weak and electromagnetic interactions should reveal parity violation, one expected a dependence of the rate of electrons scattered on an unpolarized target as a function of the helicity of the incoming electron. To enhance the rate capability, signals in the two independent detectors, a Cherenkov counter and a calorimeter, were integrated and normalized to the beam intensity for each beam pulse, and summed for the two helicity settings of the beam. The measured rate asymmetry (30), which is expected to be proportional to q^2,

$$\frac{A_{exp}}{q^2} = \frac{< Y_+ > - < Y_- >}{< Y_+ > + < Y_- >} = (-9.5 \pm 1.6) \times 10^{-5}\,\mathrm{GeV}^{-2}, \tag{2}$$

confirmed the existence of neutral currents. In the context of the Weinberg-Salam theory, this result translates to $\sin\theta_W = 0.215 \pm 0.015 \pm 0.005$, which defines the mixing of the electromagnetic and weak interactions.

From the very beginning, Panofsky provided his full support for this experiment, the most challenging ever performed at SLAC. It was based on a combination of the in-depth theoretical understanding and outstanding experimental facilities. The measurement required not only diligent monitoring of the new polarized source with random selection of polarity, but also demanded superb performance of the linac and the beam analyzing system, the precision polarimeters, and a redesign of the spectrometers and detectors.

4.3 Beyond Electron-Nucleon Scattering

As the director of SLAC, Panofsky was fully aware that the laboratory could only survive through intense accelerator research and innovation. He fostered upgrades to the linac energy, secondary beams, and novel and unique experimental facilities. The early experience with the e^-e^- storage rings was the foundation for SPEAR and later PEP and resulted in many discoveries and new insights into what is now referred to as the Standard Model of electroweak interactions. For the discoveries of the charm quark and the τ lepton Burton Richter (31) and Martin Perl (32) were awarded separate Nobel prizes. Panofsky also promoted the use of SPEAR as one of the earliest synchrotron light sources, thereby launching the development of intense photon sources as novel probes to examine micro-structures in a wide range of materials.

Panofsky stepped down as SLAC director in 1984, at a time when the linac was converted into a prototype for the next generation of high-energy e^+e^- linear colliders. Following his retirement, Panofsky devoted most of his effort to disarmament and non-proliferation of nuclear weapons, world peace, and science policy and international relations.

5 International Relations

Panofsky saw the free flow of knowledge across international borders as an avenue to foster collaboration and peace. He encouraged the exchange with scientists from around the world. Many of the prime movers at laboratories planning electron or synchrotron facilities came to work at Stanford or SLAC, and SLAC physicists spent their sabbatical leaves in Europe. Research at SLAC benefitted greatly from the participation of many scientists from abroad.

While collaborations with Europe and countries like Japan were arranged informally, cooperation with the former Soviet Union or the P.R. of China required formal bilateral agreements involving government representatives. Over many decades, Panofsky developed ties with laboratories in these countries through consultation, the formation of collaborations, and direct scientific exchange.

5.1 Interactions with Russian Scientists

During the peak of the Cold War in 1956, Panofsky, as a member of a group of prominent U.S. physicists, had a rare chance to cross the Iron Curtain and to visit a number of large research facilities, among them a nuclear reactor, the Institute for Theoretical and Experimental Physics (ITEP), and institutes of the Academy of Science. The group also visited the Joint Institute for Nuclear Research (JINR) in Dubna, an international laboratory with 18 member states, mostly from socialist countries. Panofsky was impressed by the variety of beam lines and instrumentation at JINR and ITEP, but he noticed that almost all of them were of conservative design patterned after set-ups in Europe or the U.S.A. The only exception was the laboratory in Moscow headed by Gersch Budker, where Panofsky saw pioneering plasma confinement experiments and the pursuit of pulsed magnets and other innovative technologies, many of them without near-term applications.

After Budker founded the Institute for Nuclear Physics (INP) in Novosibirsk, frequent visits were arranged for scientists in both laboratories, and a friendship developed between the two directors. Among the pioneering work by the INP group, its development of colliding beam technology was of particular interest to SLAC. In 1973, more intense discussions began between the leading scientists, Budker, Alexander Skrinsky, and V. A. Siderov on one side and Panofsky and Richter on the other. Panofsky suggested that they concentrate on a joint effort to construct and operate a 15 GeV per beam e^+e^- storage ring at Stanford. They planned on in-kind contributions from both laboratories as a way to avoid fund transfers between the two countries. The resulting proposal presented by Budker, Panofsky and Richter to the president of the Soviet Academy of Sciences was cordially received. Nevertheless, the joint activities were vetoed. Panofsky was greatly saddened by this outcome, but he realized that an international collaboration of this kind was probably premature. The two laboratories continued their scientific collaborations, INP scientists participated in various of experiments and R&D at SLAC, and SLAC outsourced the production of certain accelerator components to the INP through formal procurement procedures.

5.2 Interactions with Chinese Scientists

Contacts with China were initiated in 1973, when Zhang Wenyu, a senior member of the Institute for Atomic Energy and a leading physicist interested in high-energy physics, visited major U.S. laboratories. Zhang had been asked to advise the Chinese government on the establishment of a large high-energy physics facility. Their focus was a 50-GeV proton synchrotron, to be built near the Ming Tombs. Panofsky expressed his doubts about this proposal for an accelerator of much lower energy than the existing proton machines at CERN and at the U.S. National Accelerator Laboratory (now Fermilab). He pointed out that it would be very unlikely that this very expensive project would enable Chinese scientists to make important discoveries or innovative contributions.

Three years later, Zhang invited Panofsky for a two-week visit to China to discuss this proposal with leading Chinese scientists. Panofsky explained that an e^+e^- storage ring would be more suitable as an initial venture because such a facility would serve a dual purpose, a broad range of particle physics research plus the exploitation of synchrotron radiation, benefitting many fields of science and engineering, and at lower cost. This first visit to China was the beginning of Panofsky's intense involvement with scientists and government officials in China.

Another three years later in 1979, Chairman Deng Xiaoping and President Jimmy Carter signed the United States - China Agreement on Cooperation in Science and Technology at a ceremony in Beijing. Panofsky was a guest of honor. This agreement was followed by the establishment of the Joint Committee on Cooperation in High Energy Physics, which has met yearly ever since. Subsequently, the Chinese government agreed to sponsor the construction of the Beijing Electron-Positron Collider (BEPC) at the new Institute for High Energy Physics in Beijing.

To develop the preliminary design of BEPC, a delegation of about 30 Chinese physicists and engineers spent up to six months at SLAC. They teamed-up with various experts at SLAC to learn about all aspects of the design and fabrication of the accelerator components, and to become familiar with design and calculational tools. Soon after, they submitted a design report, and the Chinese government authorized the construction of BEPC. In the following years, Panofsky acted as a consultant and made frequent visits to Beijing. The project leader was Xie Jialin, an accelerator expert who had received his PhD at Stanford's Microwave Laboratory many years ago. In 2012 Xie received the highest science and technology award of China from Predident Hu Jintao for is outstanding life-long achievements.

The construction of BEPC was a very visible project in China. Chairman Deng Xiaoping personally lifted a shovel at the ground breaking ceremony with Panofsky at his side. High officials served as expeditors whenever difficulties were encountered, and as a result, the construction of BEPC was completed expeditiously. After a successful commissioning of the beams, the high data rates allowed a broad spectrum of studies in a unique energy range. A small contingent of U.S. scientist participated in a number of precision measurements, for instance the determination of the tau lepton mass and the absolute cross section for the production of hadronic final states as a function of the center-of-mass energy.

The success of BEPC and its research program solidified high-energy physics research in China. Furthermore, plans for dedicated synchrotron light sources in

Shanghai and elsewhere were drawn up and these new facilities have since become important research tools for material and biological sciences.

Instigated by Panofsky, studies of various options for a second generation storage ring began, a ”tau-charm factory” operating in the same energy range, but with much larger luminosity. There was now a new generation of very capable Chinese accelerator and particle physicists, and international participation became less critical. SLAC scientists served in various advisory functions. To increase the collision rate of BEPC II by more than a factor of 100, 93 bunches of electrons would collide with 93 bunches of positrons stored in two separate rings. Other improvements included a more powerful injection linac for electrons and positrons, and extensive use of superconducting technology, both for the RF-accelerating cavities and for the magnetic final focus of the stored beams entering the interaction region. All components were designed and built in China.

The detector was completely rebuilt with state-of-the-art components, including a very large compute farms. This unique facility was completed in 1998 and has attracted collaborators from Germany, Japan, Russia and the U.S.A.. The focal points of the current research program are charmonium spectroscopy, precision measurements of charm meson and tau lepton decays, and the search for rare phenomena that might indicate new physics processes. Panofsky was thrilled to witness the tremendous growth in particle physics and many other fields of science in China.

6 Arms Control and International Security

In the postwar years, Panofsky did not share the hawkish attitude of some of his colleagues and agreed with J. Robert Oppenheimer, who favored a ”go slow” on the development of a hydrogen bomb. The enormous explosive power of hydrogen weapons generated doubts in Panofsky's mind about their utility and morality, and he talked publically about the need for international agreements on such weapons.

His engagement in national security began with the "Screw Driver Report", supporting Oppenheimer's testimony in 1946 to a committee of the U.S. Senate that - given the sensitivity of detectors and effective shielding - the only sure way of detecting a shipment of one cubic inch of weapons-grade material - plutonium or highly enriched uranium - was to open the packing crate with a screw driver. This report, prepared together with Hofstadter for the AEC, contained a quantitative assessment and confirmation of Oppenheimer's statement. The threat of a suitcase bomb remains a concern today, even though the sensitivity of detection devices and signal processing have enormously improved since then.

To place the following activities in a historical contents, Table I lists the disarmament agreements between the United States and the Soviet Union.

6.1 Early Disarmament Negotiations, 1958 - 1980

In 1958, the Conference of Experts at the headquarters of the United Nations (U.N.) in Geneva, chaired by Hans Bethe and attended by scientists from the U.S.A. and U.S.S.R., published the result of extensive deliberations on a possible international agreement on the cessation of nuclear testing and means of detecting violations of such a ban. In response to Edward Teller's vociferous criticism of this report, Panofsky was asked to chair a panel of the President's Science Advisory Committee (PSAC) to assess the detection of nuclear explosions in outer space. Among the members of the panel were Bethe and Teller. To the surprise of many observers, the panel under Panofsky's leadership arrived unanimously at the conclusion that the cost of performing nuclear tests in outer space would be so enormous that any attempt by the Soviets would severely strain their national resources. Furthermore, there was a wide latitude of interpretations of backgrounds due to natural sources of radiation, such as solar winds and meteoric impacts.

Apparently Panofsky's expertise and negotiating skills were not unnoticed, and the following year marked the beginning of his fifty-year long engagement in negotiations related to nuclear disarmament (1,33). He entered the international scene as the head of the U.S. delegation to a Technical Working Group with Soviet scientists under the leadership of Yuri Fedorov, a well-respected Russian polar explorer. Their charge was to discuss the reliability of methods to detect nuclear explosions and report back within one week to the political panel overseeing the bi-lateral negotiations. These meetings were held at the U.N. in Geneva, at a time when Panofsky was on sabbatical leave to CERN. The overriding problem was the absence of an agreement as to whether the report by the Conference of Experts was a treaty or a scientific document that could be amended as new information became available. The Americans favored the latter, while the Soviets considered the document unamendable and were particularly suspicious of the Americans' attitude. As a result, the negotiations were far more protracted than expected and extended to three full weeks, which Panofsky later referred to as "the toughest three-week period of my life". He acknowledged, however, that in retrospect "they were most educational in shaping my views on arms control issues". He recognized that the intent of the Soviet delegation was to minimize any intrusive verification measures of a nuclear test ban treaty, while the Americans favored verification methods with the highest degree of confidence.

Among many suggestions, Panofsky proposed the use of highly sensitive photomultipliers to effectively detect single x-ray photons from nuclear explosions in space. This proposal appealed to the scientists of both delegations. In the end, the group reached an agreement on the assessment of this and most other verification methods. In other areas, for instance the proposal to reflect high-power RF signals off the ionosphere to detect disturbances by nuclear explosions, they agreed to disagree.

Continued protracted negotiations between U.S. and Soviet scientists and politicians led in 1963 to the Limited Test Ban Treaty (LTBT), banning tests in the atmosphere, under water, and in outer space, but not underground. It took until 1996, for the U.N. to put forward the Comprehensive Test Ban Treaty (CTBT), which the U.S. President signed, but the U.S. Senate never ratified.

In recognition of the responsibility of scientists for their inventions, the Pugwash Conferences were established in 1957 to bring together scientists and policy makers to collaborate across political divides on constructive proposals to reduce the nuclear threat. Panofsky attended a few of the Pugwash Conferences and considered them extremely useful as an informal forum for a broad range of discussions, even though most of the Soviet delegates were not totally free to voice their individual opinions.

In 1957, following the launch of Sputnik, President Eisenhower created PSAC, and charged its members to advise him on science and national security, without a filter by the parochial interests of powerful national institutions, such as the Department of Defense or the Atomic Energy Commission (AEC), or the military-industrial complex. Figure 6 shows President Eisenhower with the PSAC members. PSAC continued under President Kennedy, and Panofsky served for four years, attending plenary and subcommittee sessions in Washington every month. During this time the PSAC agenda was dominated by national security issues, for instance, ballistic missile defense, secession of nuclear tests, and the impact of radiation from nuclear explosions on the electronics of Intercontinental Ballistic Missiles (ICBM). Other topics ranged from science education and environmental protection to the lunar landing and manned space flight. Among other things, PSAC convinced the president that the manned lunar mission could not be justified as a scientific endeavor, but that it should be supported as a demonstration of America's advanced technology.

After President Kennedy's assassination, the role of science advising diminished and PSAC was dismissed by President Nixon over various disagreements, among them supersonic and nuclear driven air transport, the ballistic missile defense, and the nuclear test ban. This action underscored Panofsky's assessment that while science and government had a role in many major governmental decision, advice offered by independent scientists to the government, in particular to the President, often generated tension. He realized that the desired separation of science and politics was difficult to achieve, primarily because the forecast of the evolution of knowledge is a mixture of hard facts and judgment, and judgment is highly influenced by the political environment in which the participants find themselves. Nevertheless, he continued to serve as a consultant to the White House Office of Science and Technology until 1973.

Since the early 1950s, the issue of offensive versus defensive use of nuclear weapons kept resurfacing periodically. Though the demands of any effective antinuclear defense were and still are extremely challenging and costly, the pressure on the U.S. Government to install ICBMs to intercept the delivery of nuclear weapons persists until today. Over the years, Panofsky participated in many debates on antiballistic missiles (ABM). In his testimony to the U.S. Senate in 1969, he explained that the proposed safeguard system for the ICBM silos could easily be destroyed by a relatively limited number of Soviet missiles. Nevertheless, Congress approved the ABM deployment. Three years later, the U.S. and the U.S.S.R. signed the ABM treaty, which limited the deployment to 100 interceptor missiles on a single site in each country.

A major landmark was the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), proposed originally by Ireland and Finland. By 1970, the treaty had been signed by 190 countries, including the five nuclear weapons states (U.S., U.S.S.R. U.K, France, and China), but not including India, Israel, and Pakistan. North Korea withdrew after violating the treaty. The primary objectives were to prevent the spread of nuclear weapons and weapon technology, to promote cooperation in the peaceful use of nuclear energy, and to further the goal of nuclear disarmament. In total, 11 countries have since terminated their nuclear weapons programs.

6.2 International Security and Arms Control, 1980 - 2007

In 1980, the U.S. National Academy of Sciences (NAS) and it Soviet counterpart agreed to form a Committee on International Security and Arms Control (CISAC), of which Panofsky became a member. He was selected to be co-chair together with E. P. Velikov, from 1985 to 1993. Initially, the discussions focused on nuclear weapons, the relationship between defensive and offensive forces, and the arms race. In 1983, after detailed analyses, CISAC made public its conclusion that the defense against nuclear-armed missiles, Direct Energy Space Weapons in the form of intense laser or particle beams, would be ineffective. A week later, on the advice of Teller, President Reagan announced the Strategic Defense Initiative (SDI), calling on scientists "who gave us nuclear weapons to devise means to render them impotent and obsolete". Fortunately, General Secretary Gorbachev, after consultation with CISAC members G. A. Arbatov, R. Z. Sagdeev, and E. P. Velikov, decided not to give in to the pressure of the Soviet military and political leadership, and not to duplicate a major SDI program in the U.S.S.R.. This decision was probably the most important impact of CISAC's bi-lateral discussions, and Panofsky played a decisive role in this outcome.

In 1996, the U.N. put forward the Comprehensive Test Ban Treaty (CTBT), which by now has been signed by 189 nations, including the U.S. President. When it was brought up for ratification in the U.S. Senate, it failed. In response, President Clinton asked the NAS to conduct a study on the technical issues regarding the CTBT (34). This study, which included both technical and military analyses in which Panofsky played a leading role, concluded that the U.S. security was better served with the CTBT than without, even if compliance violations occured in North Korea, Pakistan and India. Clandestine testing by Russia or China to maintain the safety and reliability of their stockpile, though in violation of the treaty, was considered less threatening than a loss of confidence in the reliability of those weapons.

In the course of the five decades of his work related to nuclear security, Panofsky contributed in many different and often critical ways to the arms control process, negotiations of agreements and verification measures, as well as studies of the consequences of their implementation and potential non-compliance. Many of the principal CISAC reports bear Panofsky's signature in terms of clarity and thoroughness and thus constitute an enduring part of his legacy: for example, reports on the management and disposition of excess weapons-grade plutonium (35), and on the future of U.S. nuclear weapons policy (36). The monitoring of nuclear weapons and nuclear explosive materials (37) was a topic that occupied Panofsky for many years. He concluded that "present and foreseeable technological capabilities exist to support verification, based on transparency and monitoring of stocks of all categories of nuclear weapons, as well as nuclear material that are their essential ingredients".

Although CISAC was chartered to support inter-academy dialogue between the U.S. and the Soviet Union, Panofsky, who at the time chaired CISAC and had excellent relations with China, suggested that contacts be established between NAS CISAC and the Chinese Committee on Science and Technology to address arms control issues with the P.R. of China. CISAC informed their Chinese counterparts of the status of negotiations with the Soviets, and productive interactions began and continue to this day. Since then China declared a no-first-use policy for nuclear weapons. CISAC's contact with Europe, first with Italy, France and the Uniter Kingdom, and subsequently with other countries, led to the creation of the Amaldi Conferences, a forum to discuss changes and challenges of the post-Cold-War era.

In his last publication entitled "Nuclear Insecurity" in Foreign Affairs (38), Panofsky strongly criticized the defense policy which the George W. Bush administration had adopted. He reminded the reader that during the Cold War, the primary purpose of nuclear weapons was deterrence with delivery by ICBMs, strategic bombers, or submarine launched ballistic missiles. This policy was often referred to as MAD, Mutual Assured Destruction. During this period, nuclear weapons stockpile had grown to 70,000 warheads, each with 20 times the power of the Hiroshima bomb that killed 250,000 Japanese citizens, mostly civilians. The major risks of this enormous arsenal of nuclear weapons had been identified by CISAC and others as (a) accidental detonation, false alarms, and insufficient early warning systems; (b) the escalation of regional conflicts; (c) the proliferation to rogue states and terrorists; (d) the nuclear fuel cycles producing reactor-grade plutonium. Knowledge was no longer a barrier to the production of these weapons, and a few of them could threaten even a super-power. By now, the U.S. and Russia had agreed to shrink this armor to less than 3,000 warheads each.

Based on his conviction that MAD, the primary mission of nuclear weapons, had become obsolete, Panofsky pointed out that the only remaining mission of the U.S. nuclear weapons program was a very rare threat and use of such weapons by others. The vast nuclear arsenals of the U.S. and Russia were becoming more and more difficult and expensive to safeguard and also encouraged other countries to acquire nuclear weapons. He recommended that Washington and Moscow should negotiate and agree on more drastic cutbacks of their nuclear stockpile and codify these reductions in a formal treaty. The U.S. should withdraw its remaining nuclear forces from Europe, thereby sending a clear signal to Moscow. He appealed to the administration to continue the de-facto adherence to the CTBT and to take leadership by declaring and promoting a no-first-use policy. The U.S. should pursue as the ultimate goal the creation of conditions for a worldwide prohibition of nuclear weapons, acknowledging that minimal evasions of a ban were likely to continue. Achieving these goals would be a protracted process, but the U.S. had most to gain. "If we want to create a safer world for all mankind, the U.S. must engage and take leadership". There was no doubt in his mind that such a move would greatly enhance the national security of the U.S..

7 Reflections

This review covers only some of Wolfgang K. H. Panofsky's roles and accomplishments as a scientist, as the founder of SLAC, the great laboratory associated with Stanford University, and as scientific advisor to many governmental institutions in the U.S. and abroad, in particular his lifelong contributions to arms control and national and international security. Those who were close to him recognize that his impact goes well beyond the topics selected here.

Panofsky was awarded numerous honors, most notably the U.S. National Medal of Science (1969) and the Enrico Fermi Award (1979) from the U.S. Government, and ten honorary university degrees. He was elected to many honor societies, among them the U.S. Academy of Sciences (1954), the American Academy of Arts and Sciences, the Council of Foreign Relations, the America Physical Society (fellow and president 1974), and the American Philosophical Society. His contributions to international science were recognized by his election to the science academies of China, France, the U.K., Italy, and Russia.

Richard Garvin, his long-term colleague in arms-control negotiations, emphasized in his lecture to the Amaldi Conference (39) that Panofsky's "unique combination of breadth of interest, focus, energy, and talent that led to his becoming one of the great scientific advisors of the nuclear age". As stated eloquently by Jonathan Dorfan, former director of SLAC, at the Symposium *Celebrating Pief* on March 10, 2008: "To scientists of my generation, Panofsky set the gold standard. His scientific leadership and vision created the wonderful environment at SLAC in which we all could flourish".

The information presented here is partially based on Panofsky's autobiography (1) which was published post mortem, partially on presentations of many of his colleagues at the Pief Fest in 1988 (40) and other events honoring his accomplishments, and partially on scientific publications and documents on arms control negotiations and agreements, and of course, on my own recollection of personal interactions, and those of my late husband Karl L. Brown who was Panofsky's first graduate student at Stanford and his colleague for 50 years.

ABBREVIATION/ACRONYMS

SLAC	Stanford Linear Accelerator Center
UC	University of California
UCRL	UC Radiation Laboratory
RF	Radio Frequency
QCD	Quantum Chromodynamics
DIS	Deep Inelastic Scattering
NAS	National Academy of Sciences
PSAC	President's Science Advisory Committee
CISAC	Committee on International Security and Arms Control
LTBT	Limited Test Ban Treaty
CTBT	Comprehensive Test Ban Treaty
ICBM	Intercontinental Ballistic Missile
ABM	Anti-Ballistic Missiles
NPT	Non-Proliferation Treaty
SALT	Strategic Arms Limitation Talks
INF	Intermediate-Range Nuclear Force
START	STrategic Arms Reduction Treaty
MAD	Mutual Assured Destruction

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DISCLOSURE STATEMENT

The author is not aware of any memberships, affiliations, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Figure 1: Wolfgang K. H. Panofsky in the 3-km long Klystron Gallery of the Linear Accelerator. Photo by P. Ginter, Courtesy of SLAC.

Figure 2: Measurements of photons produced by negatives pions interacting in a high pressure hydrogen or deuterium target: (a) layout of the experiment, (b) photon energy spectrum from single photon and π^0 production on hydrogen, and (c) energy spectrum of single photons produced by interactions with deuterium (9). Copyright 1951, American Physical Society.

Figure 3: The 3-km long SLAC linear accelerator: (a) disc-loaded waveguide made of copper discs and cylinders, (b) the underground tunnel with the large cylindrical tube supporting the copper accelerator structure, and (c) the waveguides guides of rectangular cross section feeding the microwaves from the klystrons located in the above-ground gallery. Courtesy of SLAC.

Figure 4: Magnetic spectrometers that can rotate about the nucleon target to measure scattered electrons at different angles and energies, (a) schematic layout of the three spectrometers for 1.6 GeV covering $50-150°$, for 8 GeV covering $12-90°$, and for 20 GeV covering $1.5-25°$, and (b) the spectrometers in Endstation A. Courtesy of SLAC.

Figure 5: Deep inelastic scattering of electrons on protons: (a) diagram of the scattering process, defining the kinematic variables, (b) measured structure function W_2 as a function of the energy loss $\nu = E - E'$ for different ranges of q^2 at a fixed angle $\theta = 6^\circ$ and for $W_2 >> 2W_1 \tan^2\theta/2$. The magnified section indicates that the results in this range of ν become independent of both q^2 and ν (22). (c) The same data showing $F(x) = \nu W_2$ as a function of $x = q^2/2M\nu$, which represents the momentum distribution of the partons, as suggested by Richard Feynman. Courtesy of SLAC.

Figure 6: President's Science Advisory Committee (1960): From left to right: Standing: G. W. Beadle, D. F. Hornig, J. B. Wiesner, W. H. Zinn, H. Brooks, G. T. Seaborg, A. M. Weinberg, D. Z. Beckler, E. R. Piore, J. W. Tukey, W. K. H. Panofsky, J. Bardeen, D. W. Bronk and R. F. Loeb. Seated: J. B. Fisk, G. B. Kistiakowsky, President Eisenhower, J. R. Killian, Jr. and I. I. Rabi. Courtesy of the Dwight D. Eisenhower Library, Abilene, Kansas.

Table 1: Disarmament agreements between U.S. and U.S.S.R. (Russia) (37).

Dates	Events
1946	Baruch Plan presented to the U.N. to eliminate atomic weapons, stop their development, ensure peaceful use of nuclear power, and establish safeguards for compliance
1953	Proposal of ”Atoms for Peace” by President Eisenhower to the U.N. General Assembly
1957	Establishment of the International Atomic Energy Agency (IAEA)
1958	Begin of formal discussions on the CTBT between the U.S., U.S.S.R. and U.K.
1963	Limited Test Ban Treaty (LTBT) signed
1968	Nuclear Non-Proliferation Treaty (NPT) proposed, now signed by 189 nations
1972	Anti-ballistic Missile (ABM) treaty signed as follow-up of SALT I
1979	SALT II leads to agreements on further reduction of nuclear forces
1986	U.S. formally withdraws from SALT II, which the Senate never ratified
1987	INF treaty to eliminate intermediate and shorter range missiles signed
1991	START I signed to reduce and limit offensive nuclear arms
1993	START II to further reduce nuclear forces, signed, but never ratified by U.S.
1996	U.N. General assembly adopts CTBT, within a year 198 nations sign.
1999	U.S. Senate refuses ratification of CTBT
2001-2002	U.S. withdraws from ABM treaty, Russia withdraws from START II
2002	Strategic Offensive Reduction Treaty (SORT) signed to limit nuclear warheads
2011	New START in force to further reduce deployment of war heads, missiles, and bombers

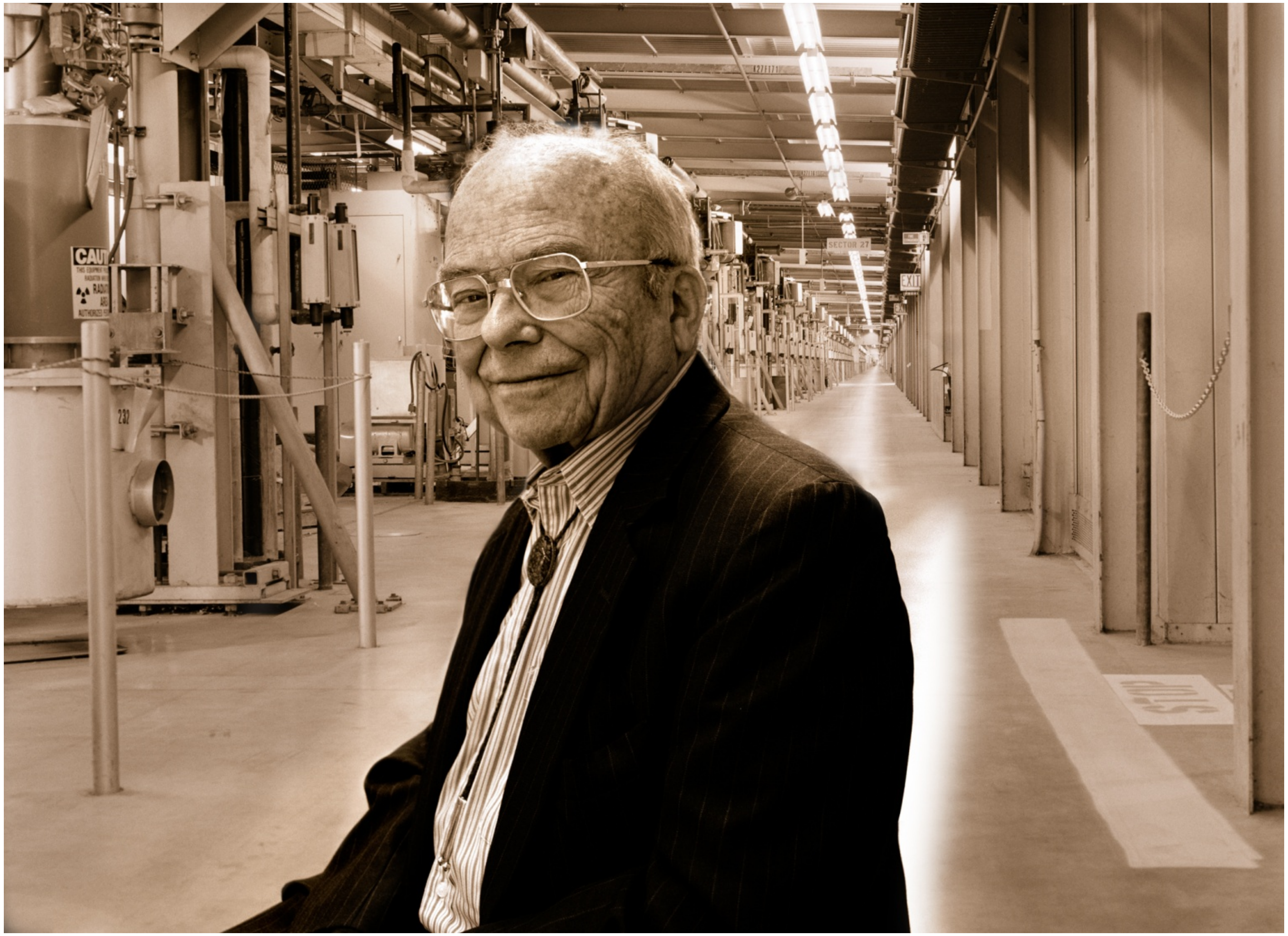

Figure 1

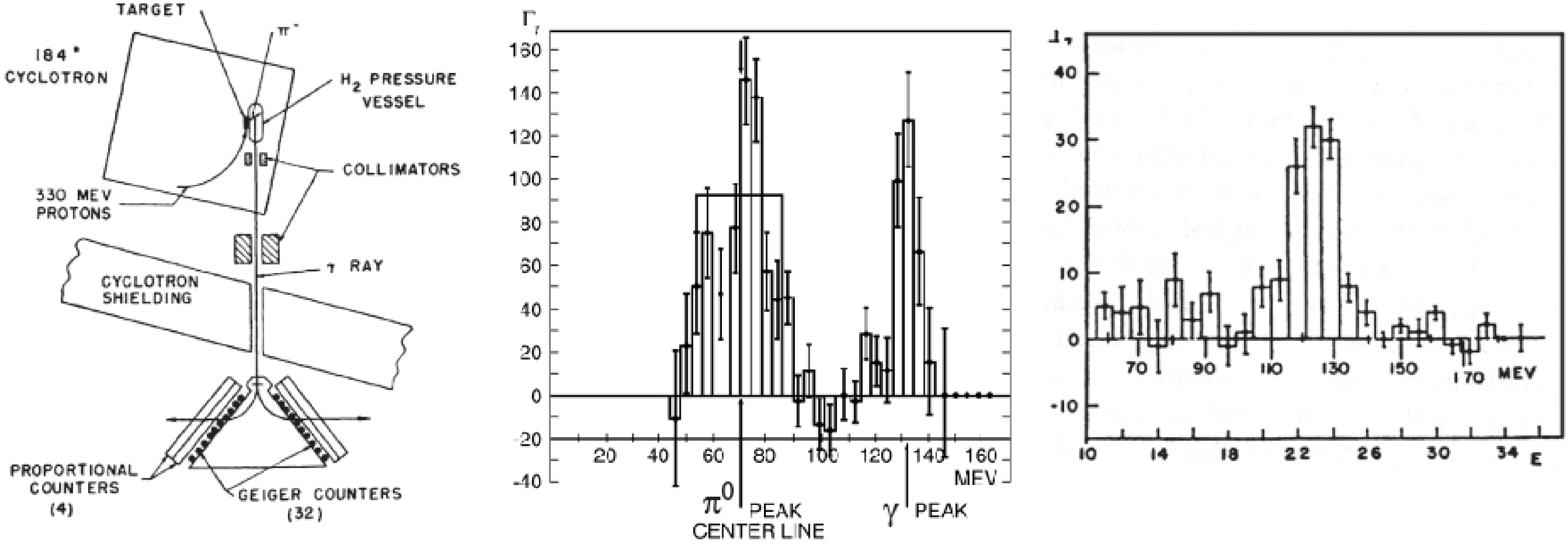
TARGET
π⁻
184" CYCLOTRON
H₂ PRESSURE VESSEL
COLLIMATORS
330 MEV PROTONS
γ RAY
CYCLOTRON SHIELDING
PROPORTIONAL COUNTERS (4)
GEIGER COUNTERS (32)
Γγ
160
140
120
100
80
60
40
20
0
-20
-40
20 40 60 80 100 120 140 160 MEV
π0 PEAK CENTER LINE
γ PEAK
40
30
20
10
0
-10
70 90 110 130 150 170 MEV
10 14 18 22 26 30 34 E

Figure 2

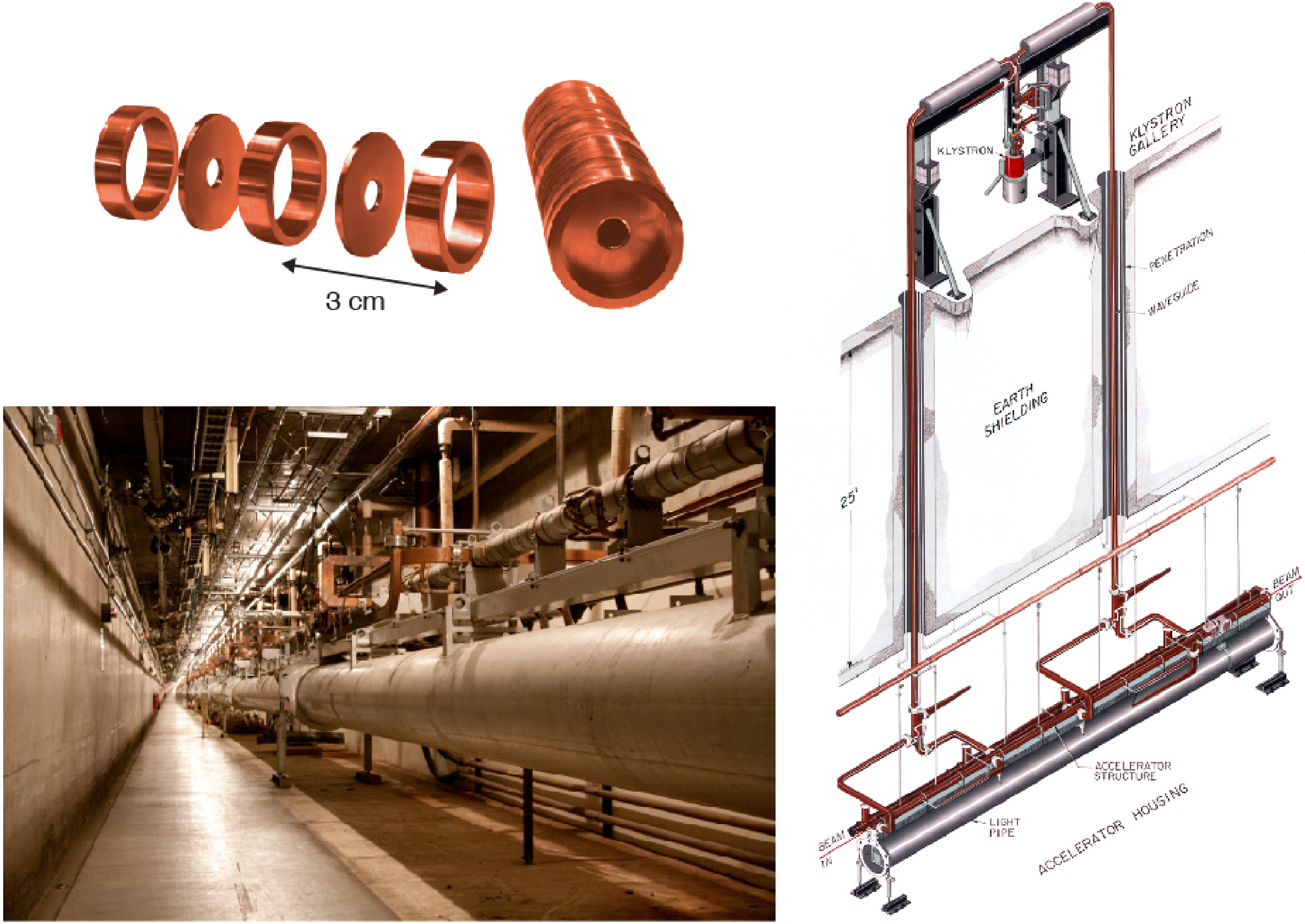
3 cm
KLYSTRON GALLERY
KLYSTRON
PENETRATION
WAVEGUIDE
EARTH SHIELDING
25'
BEAM OUT
ACCELERATOR STRUCTURE
LIGHT PIPE
ACCELERATOR HOUSING
BEAM IN

Figure 3

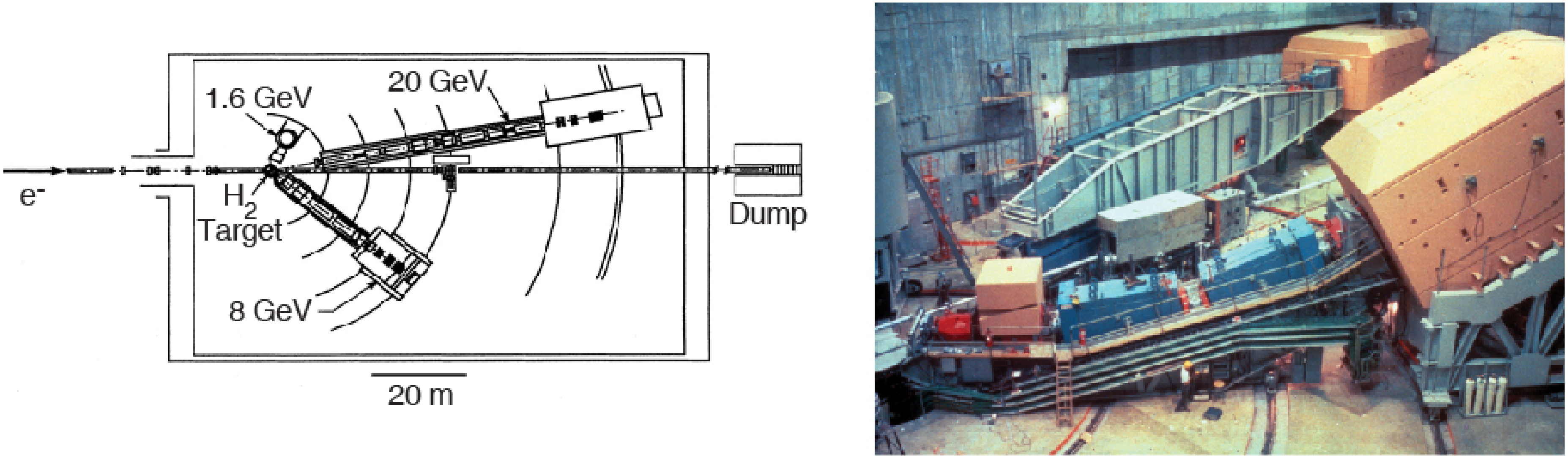

Figure 4

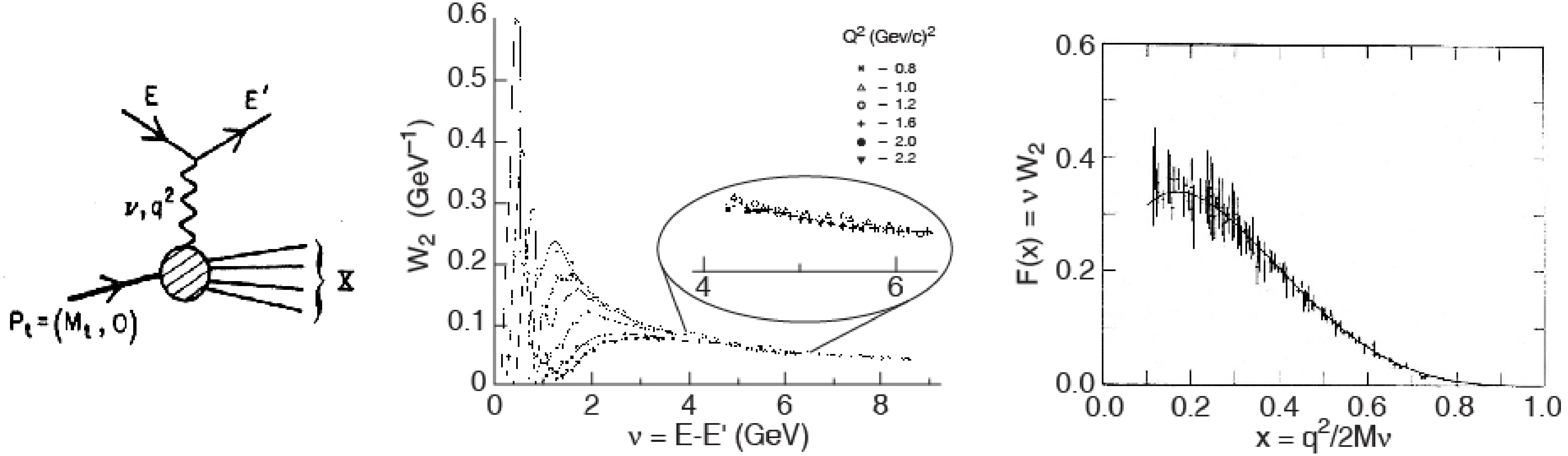
E
E'
ν, q²
P_t = (M_t, 0)
X
0.6
0.5
0.4
0.3
0.2
0.1
0
W_2 (GeV^-1)
Q² (Gev/c)²
× – 0.8
△ – 1.0
○ – 1.2
+ – 1.6
● – 2.0
▼ – 2.2
4
6
0
2
4
6
8
ν = E-E' (GeV)
0.6
0.4
0.2
0.0
F(x) = ν W_2
0.0
0.2
0.4
0.6
0.8
1.0
x = q²/2Mν

Figure 5

Figure 6