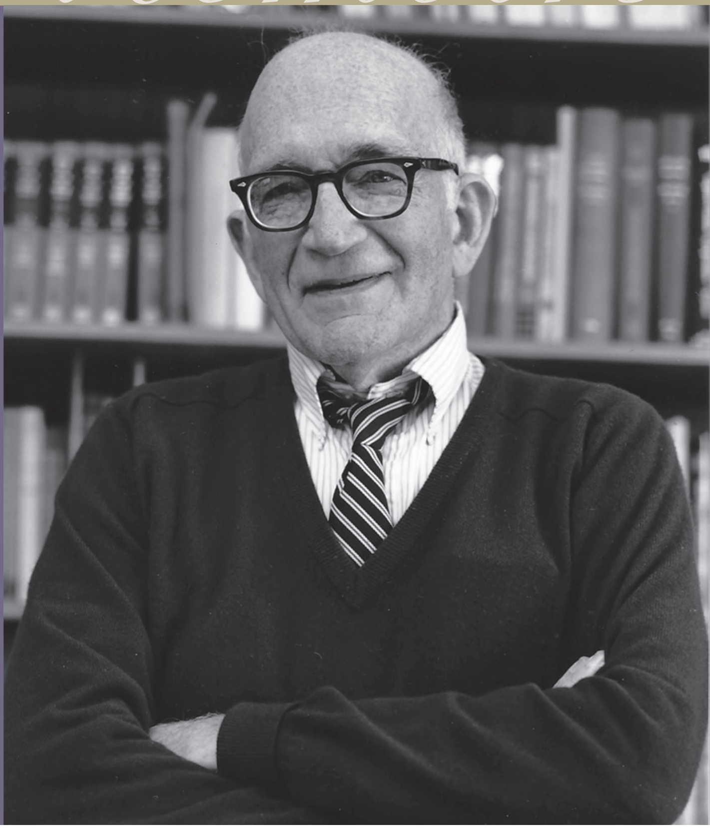
Sidney D. Drell

1926–2016

BIOGRAPHICAL *Memoirs*



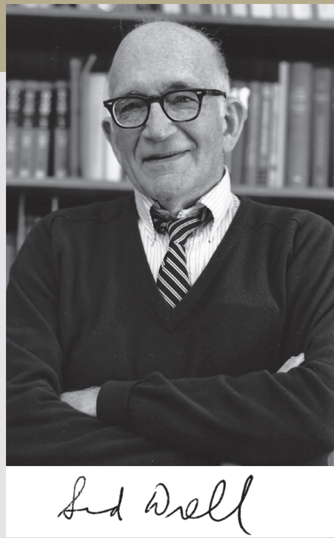
A Biographical Memoir by
Robert Jaffe
and Raymond Jeanloz

NATIONAL ACADEMY OF SCIENCES

SIDNEY DAVID **DRELL**

September 13, 1926–December 21, 2016

Elected to the NAS, 1969



By Robert Jaffe and Raymond Jeanloz

Sidney David Drell, professor emeritus at Stanford University and senior fellow at the Hoover Institution, died shortly after his 90th birthday in Palo Alto, California. In a career spanning nearly 70 years, Sid—as he was universally known—achieved prominence as a theoretical physicist, public servant, and humanitarian.

Sid contributed incisively to our understanding of the electromagnetic properties of matter. He created the theory group at the Stanford Linear Accelerator Center (SLAC) and led it through the most creative period in elementary particle physics. The Drell-Yan mechanism is the process through which many particles of the Standard Model, including the famous Higgs boson, were discovered.

Sid advised Presidents and Cabinet Members on matters ranging from nuclear weapons to intelligence, speaking truth to power but with keen insight for offering politically effective advice. His special friendships with Wolfgang (Pief) Panofsky, Andrei Sakharov, and George Shultz highlighted his work at the interface between science and human affairs. He advocated widely for the intellectual freedom of scientists and in his later years campaigned tirelessly to rid the world of nuclear weapons.

Early life[1] and work

Sid Drell was born on September 13, 1926 in Atlantic City, New Jersey, on a small street between Oriental Avenue and Boardwalk—"among the places on the Monopoly board," as he was fond of saying. Atlantic City left an indelible mark on Sid's accent, enriching his resonant voice and matching his down-to-earth style.

1 We are fortunate to have Sid Drell's perspective in his own words on many events in his life recorded by the AIP Oral History Project [Finn Asserud, Sidney Drell, Oral Histories, interviewed July 1, 1986; Francis Slakey and Jennifer Ouellette, Richard Garwin and Sidney Drell, Oral Histories, interviewed May 10, 2006.] and in a series of interviews by Ms. Lenora Ferro and Ms. Susan Schendel [Interviews with Dr. Sidney D. Drell, March 26, June 19, and July 31 2016]. We thank Ms. Ferro and Schendel for sharing their material with us.

Sid's parents immigrated to America from the Ukraine early in the twentieth century. Both were able to obtain college educations. Sid's mother Rose (White) Drell taught school before her marriage and his father Tully Drell owned a pharmacy in Atlantic City. Books, reading, and especially the classics, were a constant influence in the Drell household. Sid's father refused to allow him to help in the pharmacy during the summers, saying he wanted Sid to have free time to read books. Sid attended Atlantic City High School, where he excelled in Latin and math. He graduated in 1943 at the age of 16 and went on to Princeton University.

Sid arrived at Princeton, which was operating year round on a wartime footing, for the summer term in July 1943. Shortly after arrival, his father's illness forced Sid to seek financial aid. For the rest of his time at Princeton, Sid was supported by scholarships and by work that included waiting tables in Princeton's undergraduate eating halls. Soon Sid was both a physics major and "captain of the waiters."

During his junior year, Sid worked with Josef Jauch, an expert in the burgeoning field of quantum electrodynamics, which Sid pursued throughout his career. Jauch also introduced Sid, who had studied violin since childhood, to the pleasures of the string quartet repertoire, which became a lifelong passion.

Two events in 1945 influenced Sid for the rest of his life. He suffered a ruptured appendix and peritonitis, which at the time were life threatening, but the lasting impression came from his four months recuperating at home:[1] "In the spring of '45, the boardwalk was full of soldiers without limbs. It was terrible. When I got to the point where I could walk on the boardwalk limping along, they would assume I was one of them. But I would talk with them…and I thought I learned some of the horrors of war…It was awful." Soon thereafter, 18 year-old Sid was at the Princeton Physics Department Tea when a senior professor "…said 'I hear they just dropped an atomic bomb on Hiroshima. I hope they built a second one, put all the scientists who built the first one on an island, and drop it on them.' That was what I heard." This did not turn Sid into a pacifist ("any idea that we wouldn't use the bomb was crazy, in my mind"). Instead, the same imagination that Sid used to probe the inner secrets of the nucleus he combined with his technical knowledge to address the realities of defense and the use of modern weapons.

Sid wrote his senior thesis *Radiating Electrons* for John Wheeler, who had recently returned to Princeton, making use of a propagating action-at-a-distance formalism that Wheeler and Richard Feynman were working on at the time. Sid credited Princeton's emphasis on undergraduate research with "making a physicist out of me." So much so that in the early 1990's, when Princeton was considering eliminating its senior thesis requirement, Sid and George Shultz (Princeton '42) sent a letter to the *Alumni Weekly* passionately defending the thesis requirement, and the idea was dropped.

After Princeton, Sid entered the PhD program at the University of Illinois Urbana-Champaign, where physics was enjoying a renaissance after the war. Sid did his PhD research with Sidney Dancoff, a brilliant young theorist, who sadly died shortly after Sid finished. Sid's graduate research previewed a theme that would dominate his life's work: the interactions of electrons and photons with protons and neutrons. In his PhD thesis, Sid explored the way that the strong nuclear interactions modify the magnetic properties of nucleons. The anomalous magnetic interactions of the nucleons, in particular, would prove to be a rich vein for Sid's future theoretical explorations. Discovering the nature of protons, neutrons, and other hadrons and of the strong forces between them was a grand challenge for theoretical physics in the second half of the twentieth century—one that dominated Sid's research career.

While at UIUC in 1949 Sid met Harriet Jane Stainback. Harriet was born near Greenwood, Mississippi—a long way both physically and culturally from Atlantic City. Like Sid, Harriet had a deep affection for Latin and classical literature. After boarding school near Vicksberg, Harriet attended Wellesley College and went on to study German at UIUC. Sid and Harriet shared common interests in literature—Harriet introduced Sid to Faulkner and other southern writers—and in music. Harriet and Sid married in 1952.

Sid and Harriet Drell in California.

After completing his PhD in 1949, Sid stayed on for a year at Illinois and then in 1950 "bought a car and went West" to take up an instructorship at Stanford. Stanford was on its way to becoming a center for electromagnetic studies of hadrons. Robert Hofstadter had arrived in 1950 and begun work on electron scattering that culminated in 1953 with his discovery that nucleons are extended objects with an at-the-time unknown substructure. Soon after Sid's arrival, Pief Panofsky came to Stanford from Berkeley. Pief was to be a mentor, partner, and model to Sid throughout their long friendship. In Panofsky, Sid saw a dynamic leader who could elevate Stanford's high-


Sid Drell, BJ Bjorken, Burton Richter, and WKH (Pief) Panofsky, Stanford (SLAC).

energy physics program to prominence as well as a model for how to bear the social responsibility that came with being a physicist in the years after World War II. At Stanford, Pief focused his attention on electron scattering and Sid began to explore the related process of production of mesons by photons impinging on a proton target.

In 1952 Sid left Stanford to come to MIT to be Victor "Viki" Weisskopf's research assistant. Viki was both a pre-eminent theoretical physicist who had played a significant role in the Manhattan Project and a humanitarian who brought compassion and humility to his leadership role in the scientific world. Viki was also a superb pianist—rumor had it that he hired Sid for his skills as a violinist as well as in physics. Indeed, Sid spent many evenings playing chamber music with Viki and with Francis Low and Kerson Huang, both young MIT theoretical physicists at the time. Also at MIT, Sid met the young Israeli theoretical physicist Amos de Shalit, who was a post-doc at the time. So began a close friendship, and as well a special relationship with the Weizmann Institute of Science in Rehovot, Israel, where de Shalit helped establish the physics program. Sid's close friendship with the Weizmann Institute lasted throughout his life. He was a mentor to many Israeli high-energy physicists including Haim Harari, who later served as President of the Institute, and Shimon Yankielowicz, who served as Rector of Tel-Aviv University. Sid was a member of the Board of Governors of the Weizmann Institute starting in 1970 (Life Member as of 2006), and was on its Scientific and Academic Advisory Council from 1970 until 2012.

Sid joined MIT's faculty in 1953 and spent three productive years there before returning to Stanford in 1956. During that time quantum electrodynamics (QED) was enjoying great success. Nevertheless, Weisskopf and others were skeptical that QED would continue to be valid at distances smaller than had yet been probed. While at MIT, Drell began to consider ways to test the validity of QED at small distance scales and he turned his attention to this question in earnest upon return to Stanford.

Sid and Harriet's time in Boston was productive in other ways as well: their son Daniel, an immunologist-turned-microbiologist at the U. S. Department of Energy was born in January 1953, and their daughter Persis, also a physicist and now Provost at Stanford University, was born in 1955. Sid and Harriet's second daughter, Joanna, a medieval and Renaissance historian on the faculty at the University of Richmond, was born in 1965, after Sid and Harriet had returned to Stanford.

When the Drell family returned to Stanford, they took up residence in a rambling Queen-Anne-style house that was centrally located on the Stanford campus and in the lives of Sid's students and colleagues. In the years that followed, Sid and Harriet hosted many physics gatherings including a memorable "wake" for three theorists who had reached the milestone age of 30; students debated physics and politics around Harriet's kitchen table and babysat for Persis and then for Johanna; James "Bj" Bjorken lived on the upper floor one summer, hurrying to finish his and Sid's famous textbooks on quantum fields. Many physicists who passed through Stanford over the nearly half-century that the Drells lived on the Stanford campus remember warmly the expansive embrace that Harriet and Sid offered to their extended physics family.

Sid's return to Stanford in the summer of 1956 marked a significant shift in the center of gravity of high-energy physics. Bjorken came along as a graduate student. At the same time, Burton Richter, with a fresh PhD from MIT in experimental high-energy physics, came to Stanford for his first postdoc. With Panofsky, Drell, Richter, Bjorken, and other colleagues all at Stanford, the stage was set for the development of an electron scattering program that was destined to revolutionize our understanding of the strong forces that govern the structure and interactions of hadrons. By the late 1950's Sid had joined forces with his Stanford colleagues in a group led by Pief that was proposing to build a 20 GeV linear electron accelerator, affectionately known as the "Monster"—more than 20 times as energetic as any existing electron accelerator—nearby the Stanford campus. From the time of Sid's return to Stanford until he left active research in fundamental physics, much of Sid's work was focused on the use of quantum electrodynamics to probe the substructure of hadrons, a central issue for the Monster. Several of his papers from this era stand out for their immediate or long-term influence over the field.

Immediately upon arrival at Stanford, Sid and Bj, together with Stephen Frautschi, then a postdoc, took up the question of how to look for deviations from the predictions of QED at short distances. They showed that photoproduction of electron-positron pairs—$\gamma p \rightarrow e^+e^-p$—necessarily involves a "virtual" or short-lived intermediate photon that is sensitive to short distance modifications of QED when the pair is produced at large angles relative to the incident photon beam [1958 a, b]. This was the first of many contributions by Sid to the study of QED at short distances, work that culminated many years later in Sid's and Stan Brodsky's influential review article that surveyed the successes of QED and emphasized its fundamental importance [1970 b].

At roughly the same time Drell and Charles Schwartz published a paper that introduced two concepts into the study of the electromagnetic structure of hadrons that significantly influenced the future of the field. Earlier studies of the internal structure of the proton, carried out by Robert Hofstadter and his collaborators at Stanford, focused on elastic scattering—$e^{-}p \rightarrow e^{-}p$—where the nucleon recoils without excitation and without the production of other hadrons. The *form factors* measured in these experiments decreased rapidly with the momentum transferred from the electron to the proton. This decrease was a signal of the compositeness of the nucleon. *Inelastic scattering* in which the final proton was accompanied by one or more other hadrons, was known to become important at higher energies, but was not regarded as a promising way to learn about proton substructure. Drell and Schwartz [1958 c] showed that *inclusive* inelastic scattering of electrons from nuclei, where the final state is not observed, is sensitive to the internal structure of the initial state alone. *Inclusive inelastic scattering* of high-energy electrons from protons would lead to the discovery of quarks at SLAC a decade later.

In the same paper, Drell and Schwartz introduced the concept of a sum-rule into electron scattering from nuclear targets. A particularly elegant and insightful formulation of inelastic scattering data can be obtained by summing the scattering probability over a range of angles or another suitable variable. Typically, the complexities of the final state average out so the sum can be related to fundamental characteristics of the target such as its electric charge or spin. Such inelastic scattering sum rules had seen wide application in atomic physics. Drell and Schwartz developed sum rules for the inelastic scattering of electrons from nuclei. The application to nuclear targets was interesting in its own right, but the extension to very high energy electrons scattering from proton and neutron targets made by Bjorken and others proved critical to the discovery of quarks.

As interest in a very high-energy electron accelerator at Stanford grew toward the end of the 1950's, Sid took up the important question of whether an electron accelerator could be used to create secondary beams of high-energy hadrons. Proton-proton collisions at accelerators such as the ones at Brookhaven National Lab and Lawrence Berkeley Lab produced copious secondary hadrons that could be used in downstream experiments.

The majority of these secondary hadrons carried much lower energy than the original proton, decreasing their utility. Could an electron accelerator do better? Sid showed that a high-energy photon or electron could initiate production of secondary beams of hadrons with energy almost as high as the initial photon or electron [1960]. This phenomenon, known as the "Drell process" enabled the exploration of hadron interactions and spectroscopy at the soon to be commissioned electron accelerator at Stanford.

Nineteen sixty marked a turning point in Sid Drell's career. On the one hand, he became increasingly involved in planning for the "Monster" which became SLAC, in particular creating its nascent theory group. On the other hand, 1960 was the year Sid was invited to join the JASON group, and was thus the beginning of Sid's involvement with national service. It is an appropriate year to bifurcate this memoir.

Sid and theory at SLAC

The "Monster" became a reality in 1962 when construction of the Stanford Linear Accelerator Center began in the hills behind Stanford. Sid, Pief, and others left their positions in the Stanford Physics Department in 1963 to form the core faculty for the new lab. Sid set to work assembling the first theory group for the new Lab. Early members of the theory group included its first head, H. Pierre Noyes, along with Yung-Su "Paul" Tsai and Samuel Berman. Soon they were joined by Bjorken (1965), Stanley J. Brodsky (1966), and Frederick J. Gilman (1967), who formed the core of the group that interpreted the paradigm-shattering inelastic electron scattering experiments performed at SLAC in the late 1960's.

During the 1960's, Sid continued research connected to SLAC's mission. In 1961, Sid and Frederik Zachariasen published a slim volume on the *Electromagnetic Structure of Nucleons* [1961] that summarized what was known about the nucleon's elastic form factors. "Drell and Zachariasen" was required reading for anyone entering the field of electron scattering. Soon thereafter Sid's attention returned to *inelastic* electron scattering, the process that Sid and Schwartz had studied earlier. One of the experiments proposed for SLAC intended to explore inclusive inelastic scattering from protons and simple nuclei at the highest energies. Sid and Stanford colleague J. Dirk Walecka produced an influential paper on this subject [1964a] that prefigured a whole field of study that developed after the discovery of quarks. As was often the case with Sid's papers, the clarity of exposition in this work led to widespread adoption of its notation and methods.

Remarkably, during this very active period, Sid and Bj wrote and published their two-volume text on relativistic quantum mechanics and field theory [1964 b, 1965]. It is difficult to overstate the influence of these books on the field of high-energy physics when they were published. They were the first textbooks to present quantum field theory in a highly accessible but still relatively rigorous way, from Feynman's rules for calculation to a thorough presentation of renormalization theory. "Bjorken and Drell" dominated the field for over a decade until the appearance of textbooks that incorporated the non-Abelian gauge theories that had become central to the Standard Model of particle physics. Furthermore, "Bjorken and Drell" appeared at a time when local quantum field theory itself was out of favor among particle theorists. The texts served to educate a new generation of physicists in what would soon prove to be the enduring framework for particle physics.

As the 1960's progressed, interest in sum rules blossomed. The simple structure of electromagnetic and weak interaction currents invited relations among processes that could be converted into sum rules. Returning to his lifelong interest in the anomalous magnetic moment of the nucleon, Sid and then SLAC postdoc Anthony Hearn derived an elegant sum rule that relates the anomalous magnetic moment of any target to the difference of cross sections for absorption of photons of different polarizations [1966 a].[2]

Shortly after the appearance of the DHG Sum Rule, Bjorken published his seminal paper, which included sum rules that would be valid if the nucleon consisted of point-like constituents [Bjorken, 1966]. Although Sid was not directly involved in this work, he was among the first to recognize its importance. In a prescient remark made at the end of his rapporteur's talk at the 1966 "Rochester Conference" held at UC Berkeley [1966 b], Sid asked rhetorically "…What would I like to see measured?" and answered "…I'd very much like to see inelastic electron…cross sections measured. [They] are of great interest in their own right." In closing he added "Also, there are some sum rules, asymptotic statements derived by Bjorken and others, as to how these inelastic cross sections should behave in energy… and which can be checked experimentally." And the rest, as they say, is history! The experiments were performed by a group led by Jerome Friedman, Henry Kendall, and Richard Taylor; the asymptotic scaling laws predicted by Bjorken were verified; Bjorken's and other sum rules were eventually studied and the results led to the conclusion that hadrons are composite systems composed of quarks held together by photon-like particles now known as *gluons*. Sid was not the father of this breakthrough, but rather one of a small number of "godfathers," a group that also included Richard Feynman and Murray Gell-Mann.

2 This sum rule was discovered independently by S. B. Gerasimov [Gerasimov, 1966] and is now known as the DHG Sum Rule.

Sid, together with younger colleagues, made many contributions to understanding the dynamical significance of hadron compositeness and its implications for other processes. Not content with the rather abstract formalism of current algebra used by Bjorken and others, Sid teamed up with Tung-Mow Yan and Donald Levy to verify these results in an explicit model of nucleon substructure [1969 a, b]. This led to Sid's most lasting contribution to high energy physics: together with Yan, he showed that in high energy hadron-hadron collisions, the annihilation of the constituents—or *partons* as Feynman had named them—inside the colliding hadrons could lead to the production of very high mass states [1970]. The energy of these colliding partons could be almost entirely transformed into the mass of new particles. Now known as the *Drell-Yan process*, Drell and Yan originally studied production of very massive virtual photons that then turn into lepton-antilepton pairs. Soon, they and others realized that the same mechanism would apply to the production of any fundamental quanta that couple to the quarks and gluons that compose hadrons. Sid and Tung-Mow had made use of a model in which the ultraviolet divergences of quantum field theory were ignored. Although artificial, the model retained the essential physics. When quark and gluon interactions became better understood and the results of [1970] were slightly modified, Sid's and Tung-Mow's work was dubbed the "*naive* Drell-Yan" process. Sid never accepted the moniker "naive," and rightly so, since the process could not have been discovered in those days without suppressing ultraviolet divergences.[3] The $W^{\pm}$ and Z bosons that mediate the weak interactions and the Higgs boson that completed the Standard Model were all first produced in high-energy hadron colliders through the Drell-Yan process. It remains the primary mechanism by which physicists at high-energy hadron colliders such as the *Large Hadron Collider* (LHC) at CERN hope to create heavier and more fundamental constituents of matter.

After 1970, Sid went on to help elucidate the quark substructure of hadrons [1975], to explore variational and lattice formulations of quantum field theory, to search for further layers of substructure [1980], and to describe the radiation that is emitted when packets of electrons and positron pass through one another in a high energy e^+e^- collider. After the early 1970s, however, Sid turned more and more of his attention to the public service and humanitarian work that is described in the next section of this memoir.[1]

Sid was a dominant figure in the SLAC Theory Group from its inception. He formally led it for thirty years starting in 1969 when he was appointed Deputy Director.

3 For experts: The DY process does not follow from Wilson's operator product expansion alone, but instead requires the full apparatus of asymptotically free quantum chromodynamics, which was not in place until 1973.

Sid's Theory Group was—and still is—renowned for its creative energy, its casual atmosphere, and its open welcome to graduate students, postocs and visitors, all of which were encouraged by Sid. His booming voice could often be heard resonating in the corridors as he tracked down a collaborator or debated a point of physics. Sid initiated a student seminar, held weekly in SLAC's *Green Room*, to which no one with a PhD, except Sid, was invited. Sid justified this by asserting that he left his PhD outside the door and promised to ask only the stupidest questions. These seminars were a memorable experience for all the students who passed through SLAC during Sid's reign. Postdocs and visitors also thrived when Sid led the SLAC Theory Group. Indeed, it was considered a "paradise for postdocs" in those days. In addition, Sid together with Burt Richter instituted a yearly "theorists versus experimenters" softball game on the lawn outside SLAC's Central Lab building. Sid played catcher for the theorists—a particularly harrowing position given the number of foreign physicists who hadn't the slightest idea what to do with a bat! His irrepressible good cheer made up for the fact that the theorists usually lost and that the trophy commissioned by Richter for the most part remained safely in the hands of the experimentalists.

Over his career, Sid had many graduate students who went on to successful careers in physics. A partial list includes Richard Blankenbecler (SLAC, emeritus), Bj Bjorken (SLAC, emeritus), Heinz Pagels (Rockefeller University, deceased), Jeffrey Royer, Joel Primack (UC Santa Cruz, emeritus), Dennis Silverman (UC Irvine, emeritus), Michael Creutz (Brookhaven National Lab, retired), Robert Jaffe (MIT), and Roscoe Giles (Boston University).

Policy, National Security, and Human Rights

Five activities highlight Sid's involvement with policy, security and human rights: i) helping found JASON in 1960; ii) serving on the President's Science Advisory Committee (PSAC, 1966-71) and President's Foreign Intelligence Advisory Board (PFIAB, 1993-01); iii) befriending and becoming a prominent supporter of Andrei Sakharov and Elena Bonner (1974 onward); iv) chairing a Panel on Nuclear Weapons Safety for the U.S. Congress (1990-91); and v) (starting in 2006) helping to initiate the Shultz-Perry-Kissinger-Nunn initiative for a world free of nuclear weapons. Over this time period, Sid also provided leadership to the scientific research community, notably as member and chair of the DOE High Energy Physics Advisory Panel (HEPAP: 1974-85), and as President of the American Physical Society (1986).

Charles Townes, then at the Institute for Defense Analysis, called Sid in January 1960 with the request to help form a new group of academic scientists who would advise the U.S. Government on matters of national security.[1] The JASON group being formed under the leadership of Marvin Goldberger was intended to develop a new generation of scientific experts to provide independent advice to the government, succeeding those who had been involved in the Manhattan Project and other scientific efforts for the military during World War II.

Sid was busy with his research, teaching, and family life, but he knew Townes by reputation and felt honored by the invitation. He was also influenced by Pief Panofsky, whose government service Sid admired, not just his involvement in the Manhattan Project and subsequent advising the U.S. Government, but also Pief's resigning from the University of California to protest the 1950 Loyalty Oath. In fact, Sid had been surrounded for years by leading academics advising the government: Wheeler, Weisskopf, and Panofsky, among others.

Sid joined JASON in 1960, working with Malvin Ruderman that summer to consider whether a high-altitude nuclear explosion could prevent satellite detection of subsequent missile launches.[1] He was soon engaged with PSAC, starting as a consultant in 1963 and continuing through as a PSAC member until 1971, at which point he was meeting regularly with National Security Advisor Henry Kissinger.

Sid had quickly become interested in the emerging field of satellite imagery, and one of his memorable efforts was on a PSAC Panel chaired by Edwin Land that informed the President's Science Advisor on strategic reconnaissance. Sid was involved in deciphering why early satellite imagery was of mixed quality, due to electrostatic charging of the photographic film in space. He would later joke: "We discovered the corona effect in the Corona satellite." From 1969 to 1993 he was at various times advising the U.S. Arms Control and Disarmament Agency, National Security Council, Congressional Office of Technology Assessment, Office of Science and Technology Policy, Department of Energy, and Senate Select Committee on Intelligence.

Much of this work was outside the public domain, but it was during this same period that Sid became visible in the human rights arena because of his relationship with Andrei Sakharov.[1] They met in 1974, at a conference on quarks and partons in Moscow, and later shared a "last supper" before Sakharov went on a hunger strike to protest travel restrictions in the Soviet Union. Exile to Gorky in 1980 meant Sakharov became less visible to the world at large, hence reducing his impact at home. Even then Sid maintained a crucial channel of communication both to keep the scientific community aware of Sakharov's circumstances and to inform Sakharov that the outside world was paying attention. "I think the man will go down in history books along with Gandhi, Martin Luther King and other people like that in this century."[1] Years later, Sid and George Shultz organized a conference celebrating Sakharov's accomplishments in human rights, which rival if not surpass his prodigious contributions to science and technology [2015].

In the meantime, concerns about safety of the weapons and procedures associated with the U.S. nuclear arsenal led the House Armed Services Committee to request a study in 1990, to be conducted by Sid along with John Foster, Jr. (former Director of the Lawrence Livermore National Laboratory) and Charles Townes. Foster recalled that Sid: "was an excellent chairman, thorough and kept digging deeper, relentlessly to get to the bottom of matters…I thought we did have the necessary impact with the safety study—Sid did everything he could do. I came from a different perspective, and it all came together due to Sid's leadership.[4] The study did document problems that needed to be rectified [HASC Panel, 1990], and was accompanied by news accounts about U.S. nuclear artillery shells being quietly returned from foreign deployment due to safety concerns.

Andrei Sakharov and Sid Drell, Stanford.

The study also introduced Sid to Robert Peurifoy, who had particular expertise in safety of U.S. nuclear weapons [Peurifoy, 2012]. They were kindred spirits, ruthlessly committed to technical accuracy even when the consequences were politically challenging. They teamed up in considering the needs of the U.S. nuclear-weapons complex, which helped lay the foundation for the Stockpile Stewardship Program.

Arguably the most important JASON studies that Sid led were those formulating Stockpile Stewardship, and concluding that the U.S. arsenal could be maintained without resort to nuclear-explosion testing [JASON, 1994, 1995]. The studies thus provided technical support for the United States endorsing the Compre-

4 Personal communication to R. Jeanloz, January 18, 2017.

hensive Nuclear-Test-Ban Treaty (CTBT), and in 1996 the U.S. was the first signatory to the CTBT. However, the Senate voted not to support ratification in 1998. Here is Sid on research scientists working at the interface with public policy (though in a slightly different context):[1]

> *You go in with one motive, but the way the fruits of your labor will be used or put into policy can be very different....The laws of physics are fixed. The laws of politics change. And you're supping with the Devil in a difficult way. It's to be expected. It's unavoidable. And you have to have your guard up.*

In this same time period, Sid was serving on PFIAB, about which little can be said except that, among other efforts, he worked closely with (retired) Senator Warren Rudman on a study that had considerable impact on the U.S. nuclear weapons complex, including creation of the "quasi-independent" National Nuclear Security Administration [PFIAB, 1999]. A workshop in recognition of his "retirement" ("Sid Fest"), held at SLAC on July 30, 1998, featured greetings from President Clinton and the following from Panofsky: "The government needs independent experts, and we are fortunate that Sid is both."

As in academic research, Sid was a mentor to many scientists engaged with policy-relevant work, expressing the following about JASON:[1]

> *I personally think the biggest impact has been creating a generation of scientists...who have had an impact through their direct involvement, either because of the studies they did which then caused defense scientists or parts of the Defense Department to see things better, or because we've entered the public debate...to the extent that it's made some of us into independent public players in the process, its overall impact has been crucial, and I'd hate to see it lost.*

With this perspective, it is understandable that Sid was supportive of similar initiatives being started in other democratic countries, the idea being that policy benefits from having a sound technical foundation and also from being exposed to independent outsiders who are skeptical by nature, as is the case with research scientists.

His focus on students and cross-disciplinary approaches are reflected in the arms-control program Sid started in 1970 with John Lewis at Stanford. Now the Center for International Security and Cooperation, it is still co-directed by a natural scientist and social scientist, and became a template for similar programs in other universities. It is notable that Sid worked on problems ranging from biological weapons (with Joshua Lederberg) to the safety of nuclear power plants, and that his collaborations extended to the religious communities, from Father Bryan Hehir beginning when he was serving the U.S. Catholic Conference of Bishops, to (Episcopal) Bishop William Swing starting when he was Bishop of California.

Sid's passion for the last dozen years of his life was promoting the vision of a world free of nuclear weapons [Taubmann, 2012]. He became close friends with George Shultz starting in 1989, when Shultz returned to Stanford upon completing his term as Secretary of State. Over time, they developed views on the post-Cold War era being the time to start ridding the world of nuclear weapons, bolstered by the increased recognition after 2000 that terrorism and cyber attacks can pose significant threats to nations.

George Shultz and Sid Drell, Stanford (Hoover).

Sid had been thinking about nuclear arms reductions for years. For example, the 1993 book with former National Security Advisor McGeorge Bundy and (retired) Admiral William Crowe, Jr. describes a U.S. nuclear arsenal of 1000-1500 [1993], and similar numbers are presented in a 2005 study with Ambassador James Goodby [2005]. Sid considered nuclear weapons to be "weapons of last resort," and felt that "no-first-use" commitments have little credibility.

By 2006, Shultz had pulled together a core group, including former Secretary of State Henry Kissinger, former Secretary of Defense William Perry, and former Senator Sam Nunn; Sid provided technical leadership. Their objective was to develop a vision for, and path toward, a world free of nuclear weapons. They started with a workshop on the twentieth anniversary of the Reykjavík Summit, reviewing the circumstances of this 1986 meeting at which President Reagan and General Secretary Gorbachev considered getting rid of both U.S. and Soviet nuclear arsenals [2007].

The result was a prominent editorial in the Wall Street Journal [Shultz, et al., 2007], for which Sid had considerable responsibility but felt no need to be a co-author: "Readers will recognize those four names, not mine." Other meetings followed at Stanford and around the world, as did additional public statements by the four renowned statesmen, with Sid in the background but occasionally included. One can see echoes of this effort in President Obama's 2009 Prague speech, in the Pope's 2015 position on nuclear weapons, in the 2017 Nobel Peace Prize recognizing the International Campaign to Abolish Nuclear Weapons, and in the current United Nations debate about a treaty on the prohibition of these weapons. The story is unfolding, and history will have to judge Sid's influence on how effectively humanity comes to terms with nuclear weapons or—for that matter—other powerful technologies that we are in the process of developing at what seems to be an increasing pace.

MEMBERSHIPS

American Physical Society

National Academy of Sciences

American Academy of Arts and Sciences

American Philosophical Society

Academia Europaea

AWARDS AND HONORS

1961–1962 and 1971–1972. Guggenheim Fellowship

1972. Ernest Orlando Lawrence Memorial Award for research in theoretical physics (Atomic Energy Commission)

1973. University of Illinois Alumni Award for Distinguished Service in Engineering

1988. University of Illinois Alumni Achievement Award

1978. Richtmyer Memorial Lecturer to the American Association of Physics Teachers, San Francisco, California

1979–1984. Lewis M. Terman Professor and Fellow, Stanford University

1980. Leo Szilard Award for Physics in the Public Interest presented by the American Physical Society

1981. University of Illinois. Honorary Doctorate.

1983. Honoree of the Natural Resources Defense Council for work in arms control

1984–1989. Prize Fellowship of the John D. and Catherine T. MacArthur Foundation

1993. Hilliard Roderick Prize in Science, Arms Control, and International Security of the American Association for the Advancement of Science

1994. Woodrow Wilson Award, Princeton University, for "distinguished achievement in the nation's service"

1994. Corecipient of the 1989 "Ettore Majorana - Erice - Science for Peace Prize"

1995. John P. McGovern Science and Society Medalist of Sigma Xi

1996. Gian Carlo Wick Commemorative Medal Award, ICSC–World Laboratory

1997. Distinguished Associate Award of U.S. Department of Energy

1998. I. Ya. Pomeranchuk Prize, Inst. of Theoretical and Experimental Physics, Moscow

1999–2000. Linus Pauling Medal of Stanford University

2000. University of California Presidential Medal

2000. One of 10 scientists honored as "Founder of national reconnaissance as a space discipline" by the U.S. National Reconnaissance Office

2000. Enrico Fermi Award, presented on behalf of the president of the United States and the secretary of the U.S. Department of Energy, for lifetime achievement in nuclear energy

2001. Tel Aviv University. Honorary Doctorate.

2001.Weizmann Institute of Science. Honorary Doctorate.

2001. National Intelligence Distinguished Service Medal, the U.S. intelligence community's highest honor, presented by the director of central intelligence at the CIA

2001. William O. Baker Award for contributions to national security, particularly in the field of foreign intelligence, sponsored by the Intelligence and National Security Alliance (INSA)

2001. Heinz R. Pagels Human Rights of Scientists Award, New York Academy of Sciences

2005. 11th annual Heinz Award for Public Policy, Washington, D.C.

2008. American Academy of Arts and Sciences Rumford Prize

2008. Stanford University Pioneers in Science

2012. National Nuclear Security Administration's Gold Medal of Excellence

2013. National Medal of Science

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Gerasimov, S. B. 1966. A sum rule for magnetic moments and the damping of the nucleon magnetic moment in nuclei. *Sov. J. Nucl. Phys.* 2:430.

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President's Foreign Intelligence Advisory Board (PFIAB). 1999. Science at Its Best, Security at Its Worst: A Report on Security Problems at the U.S. Department of Energy. Available online at https://energy.gov/sites/prod/files/cioprod/documents/pfiab-doe.pdf.

Shultz, G. P., W. J. Perry, H. A. Kissinger, and S. Nunn. 2007. A world free of nuclear weapons. *Wall Street Journal*, January 4.

P. Taubman. 2012. *The Partnership: Five Cold Warriors and Their Quest to Ban the Bomb*. New York: Harper Collins.

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b) Quantum electrodynamics at small distances. *Ann. Phys.* 4:75.

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1960 Production of particle beams at very high energies. *Phys. Rev. Lett.* 5:278.

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1964 a) With J. D. Walecka. Electrodynamic processes with nuclear targets. *Annals Phys*. 28:18.

b) With J. D. Bjorken. *Relativistic Quantum Mechanics*. New York: McGraw Hill.

1965 With J. D. Bjorken. *Relativistic Quantum Fields*. New York: McGraw Hill.

1966 a) With A. C. Hearn. Exact sum rule for nucleon magnetic moments. *Phys. Rev. Lett.* 16:908.

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b) With D. J. Levy and T. M. Yan. A theory of deep inelastic lepton-nucleon scattering and lepton-pair annihilation processes. 1. *Phys. Rev.* 187:2159.

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b) S. J. Brodsky and S. D. Drell. The Present Status of Quantum Electrodynamics. *Ann. Rev. Nucl. Sci.* 20:147.

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2007 With G. P. Shultz, S. P. Andreasen, and J. E. Goodby (eds.). *Reykjavik Revisited: Steps Toward a World Free of Nuclear Weapons*. Stanford, CA: Hoover Institution Press.

2015 *Andrei Sakharov: The Conscience of Humanity.* With G. P. Shultz (eds.). Stanford, CA: Hoover Institution Press.