Leo Szilard in Physics and Information

by

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Abstract:

The excellent biography[1] *by William Lanouette, ``Genius in the Shadows," tells it the way it was, incredible though it may seem. The 1972 ``Collected Works of Leo Szilard: Scientific Papers," Bernard T. Feld and Gertrud W. Szilard, Editors, gives the source material both published and unpublished. Szilard's path-breaking but initially little-noticed 1929 paper, ``On the Decrease of Entropy in a Thermodynamic System by the Intervention of Intelligent Beings" spawned much subsequent research. It connected what we now call a* bit *of information with a quantity* k ln 2 *of entropy, and showed that the process of acquiring, exploiting, and resetting this information in a one-molecule engine must dissipate at least* kT ln 2 *of energy at temperature* T. *His 1925 paper, ``On the Extension of Phenomenological Thermodynamics to Fluctuation Phenomena," showed that fluctuations were consistent with and predicted from equilibrium thermodynamics and did not depend on atomistic theories. His work on physics and technology, demonstrated an astonishing range of interest, ingenuity, foresight, and practical sense. I illustrate this with several of his fundamental contributions to nuclear physics, to the neutron chain reaction and to nuclear reactors, and also to electromagnetic pumping of liquid metals.*

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[1] “Genius in the shadows: a biography of Leo Szilard : the man behind the bomb” by William Lanouette and Bela Silard (1992 and 2013), henceforth abbreviated as “[WL]”

I met Leo Szilard, from 1947 to 1952 at the University of Chicago where I saw him in the faculty seminar run by Bill Libby, in his lab with Aaron Novick, eventually at dinners, and later, on occasion, in New York or Geneva.

A few personal encounters

I visited Leo in his laboratory at the Institute for Radiobiology and Biophysics, which occupied a new building where I had my office from 1950. There Leo showed me the "chemostat," an ingenious and powerful tool he had invented and developed with Aaron Novick. I recall Leo's telling me that they had had concern that polyethylene, insulator of high-performance coaxial cables developed during the war, might live forever, immune to degradation by microbes. Apparently, though, they had "trained" microbes to degrade polyethylene (less outrageously—had directed the evolution of microbes by manipulating their environment in the chemostat).

After I had been to Los Alamos as a consultant for the first of many summers in 1950-52, before moving from the Physics Department at the University of Chicago in December 1952 to the new IBM Watson Scientific Laboratory at Columbia University, at a party at the home of Mildred and Murph Goldberger, Edward Teller told me of the high regard in which he held Leo Szilard. He said, "You know the way I use Freddie De Hoffman for calculations at Los Alamos; that is how Leo uses me." Leo Szilard's ingenuity and inventiveness outclassed those of Edward Teller.

I learned from Bill Lanouette's book that Leo from the beginning was a would-be social engineer, devising schools, political organizations, even systems of money to avoid or solve society's problems. After the wartime work of the Metallurgical Laboratory at the University of Chicago was largely done, Leo had time to think further about the implication of the nuclear weapon soon to be tested at Alamogordo. That led him to a lifelong career in arms control, in which he was uniquely and personally involved.

At the time of the Cuban Missile Crisis, Leo was passing through New York and asked me to meet him in Manhattan at a small restaurant for dinner. The newspapers were full of the charge that the Soviet Union had installed nuclear-armed rockets in Cuba, and Leo and I politely disagreed on the likelihood. Leo felt that they would *not* have done such a thing because they had nothing to gain from it. My position was that they probably *had* installed such missiles because they had nothing to lose. Of course, we were both wrong. The Soviet Union *had* installed intermediate range nuclear missiles, and they *did* have a lot to lose from it. The crisis was peacefully resolved, with the Kennedy Administration withdrawing U.S. nuclear missiles from Turkey and Italy, as a never-admitted compensation for the removal of Soviet nuclear weapons from Cuba.

When I encountered Leo having an espresso in the CERN cafeteria, we arranged to meet for dinner at the Buffet de la Gare des Eaux Vives on the left bank. I recall that Leo ate only green beans for that dinner; our topic of discussion was his suggestion to publish lists of ranking of cities so that if the Soviet Union destroyed a U.S. city during nuclear war, the U.S. would have the "right" to respond or at least the expectation of response by destroying the equivalent Soviet city. I suggested that the response should be the destruction of a city half as valuable, which would have comparable deterrent effect, but would at least, if continued indefinitely, result in finite rather than infinite destruction, limited to twice the value of the city first lost.

But now for the meat of this presentation, some illustration of the technical content of Leo Szilard's work. For this, I depend largely on "The Collected Works of Leo Szilard—Scientific Papers"[2]—henceforth referred to as [CW].

Leo Szilard was an intensely practical person as well as a visionary. He saw immediate solutions to problems, but, confident that the problem would be solved, he looked many steps beyond, to the applications. Thus, with Albert Einstein, in 1930 Leo patented an electromagnetic pump with no solid moving parts or non-metallic seals, inducing currents in a liquid metal that would pump the metal without the wasteful eddies and turbulence characteristic of previous approaches to electromagnetic pumping; this was proposed for use in household refrigerators[3].

Leo then worked with the General Electric Company of Germany to put this invention into practice, one of its advantages being the absence of noise from rotating machinery. Unfortunately, the alternating forces and pressures involved proved to be a much greater noise source, and for various reasons the electromagnetic pumps never found a role in refrigeration. Part of the problem was competition from sealed units in which the motor as well as the pump were within the metallic boundary of the system, so that the only seals involved were

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[2] "The Collected Works of Leo Szilard: Scientific Papers," Bernard T. Feld and Gertrud Weiss Szilard, Editors, 1972.

[3] [CW 540-541]

elastomeric or glass-metal feed-throughs for electrical current, and even those could have been replaced by transformer coupling through a thin stainless steel boundary.

Szilard and Einstein went on to patent the intensely practical absorption refrigerator[4].

Szilard in nuclear physics and nuclear weapons

Early on, Leo deduced that if he were to achieve his potential he would have to avoid domestic ties and the drag of possessions, including a home. So he lived in hotel rooms and later in faculty clubs almost his entire life. He had cultivated physicists throughout Europe and Great Britain and would call by telephone or communicate by mail or telegraph. He was an inveterate reader and attended lectures. So he learned immediately of Chadwick's discovery of the neutron in 1932 and that year read H.G. Wells' *The World Set Free*, published in 1914.

In 1933 Leo was living in the Imperial hotel, on London's Southhampton Row. Waiting at a traffic signal to cross the road, he was pondering a recent comment by Lord Rutherford, published in *The Times* of September 12, 1933,

> *"We might in these processes obtain very much more energy than the proton supplied, but on the average we could not expect to obtain energy in this way. It was a very poor and inefficient way of producing energy, and anyone who looked for a source of power in the transformation of the atoms was talking moonshine."*

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[4] E.g. USP 1,781,541 of Nov. 11, 1930.

and worried it not quite to death but to an advanced state of ill health.

Szilard asked himself why there should not be one of the elements which, when exposed to neutrons would undergo a nuclear reaction that would produce two neutrons. He immediately conceived a search for such *(n,2n)* reactions and decided not to enlist the "know-too-much" physicists, but to look for a willing chemist.

Leo filed a patent application in the UK and requested that it be kept secret. Szilard never did obtain the promised £2000 to explore the periodic table (having mentioned beryllium, uranium, and thorium in his patent). General Electric (USA) told him,

> *That his "larger issue" of power production—the chain reaction—"is so far outside the scope of a company's normal activities, that unless the proposition takes some much more definite shape, it would be impossible to participate." [WL-148]*

Leo was not idle, though, and with no background in nuclear physics immediately began to exploit the neutron. His first paper in the field, with T.A. Chalmers (1934)[5], took advantage of Szilard's perception that a nucleus that suffers a nuclear reaction would recoil to such an extent that it would break its chemical bond.

They worked with ethyl iodide and added a bit of free iodine to stabilize any iodine that would be produced by recoil, demonstrating that a large fraction of the radioactive material created by exposure to neutrons could be extracted from the ethyl iodide as free iodine. This constituted a

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[5] "Chemical Separation of the Radioactive Element from its Bombarded Isotope in the Fermi Effect," L. Szilard and T.A. Chalmers, *Nature*, 134:462 (1934) (Letter). [CW 143-4].

new and effective means of isotopic separation and established a convenient and powerful tool for research and production of medical isotopes.

In 1934, Szilard and Chalmers used their ethyl iodide preparation as a neutron detector to demonstrate[6] that beryllium produced neutrons under the influence of radium gamma rays. And in December 1934 by the use of bromoform arranged to be exposed to the radiation from beryllium excited by 1.5 megavolt x-rays in Berlin and flown from Berlin to London, Szilard and his colleagues separated[7] radiobromine from the stable chemical to show that neutrons were produced from beryllium by energetic x-rays..

In January 1935, “Radioactivity Induced by Neutrons,”[8] Szilard and Chalmers noted that a four-hour neutron-induced radioactivity in indium was not sensitive to the presence of water (hence not due to slow-neutron capture), and discovered the In^{115m} (336 keV) isomeric activity excited by inelastic scattering of fast neutrons.

In December 1935, “Absorption of Residual Neutrons,”[9] Leo Szilard published the only paper in nuclear physics for which he had no collaborator. His point was that neutrons not absorbed by cadmium generated radioactivity in indium (54-minute period) and that this induced radioactivity was due to neutrons that are strongly absorbed by indium. This was the first indication of resonance absorption.

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[6] “Detection of Neutrons Liberated From Beryllium by Gamma Rays: A New Technique for Inducing Radioactivity,” L. Szilard and T.A. Chalmers, *Nature* **134**, 494 (1934) [CW [145-146]

[7] “Liberation of Neutrons from Beryllium by X-Rays:Radioactivity Induced by Electron Tubes,” A. Brasch, et al, *Nature,* 134:880 (1934) [CW 147-158]

[8] “Radioactivity Induced by Neutrons,” L. Szilard and T.A. Chalmers, *Nature*, 135:98 (1935) (Letter). [CW 149].

[9] “Absorption of Residual Neutrons,” *Nature*, 136:950-951 (1935) (Letter). [CW 150-152].

In the pre-fission era of nuclear physics (i.e., pre-Christmas-1938), Szilard had two more papers—one of February 1937 ("Gamma Rays Excited by Capture of Neutrons"[10]) in which he pioneered the use of the neutron "howitzer" to determine, that elements from atomic weight 35 to 200 give similar numbers of gamma rays when they capture a neutron.

With Maurice Goldhaber and R.D. Hill in a February 1939 paper[11], Szilard pins down the excited metastable state, In^{115m}, of stable In^{115}, showing that it can be produced from In^{115} by 2.5 MeV neutrons but not by strong sources of photoneutrons with energy ten times lower. They also showed that In^{115m} was produced by the radioactive decay of Cd^{115}.

In the post-fission era, Szilard's first paper of April 1939, with Walter H. Zinn, "Instantaneous Emission of Fast Neutrons in the Interaction of Slow Neutrons with Uranium"[12] used a helium-filled ionization chamber to establish that the delay time for the "instantaneous emission" was less than about one second. They also established that any delayed neutrons constituted less than about 0.1% of the fast neutrons, with the (unstated) assumption that the delayed neutrons had the same energy spectrum as the instantaneous neutrons.

Without multiplying indefinitely Szilard's papers and contributions to the pre-Manhattan-Project nuclear program, I refer to his February 6, 1940 submission to The Physical Review,

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[10] "Gamma Rays Excited by Capture of Neutrons," J.H.E. Griffiths and L. Szilard, *Nature*, 139:323-324 (1937) (Letter). [CW 153-154].

[11] "Radioactivity Induced by Nuclear Excitation: I. Excitation by Neutrons," M. Goldhauber, R.D. Hill and L. Szilard, *Phys. Rev.*, 55:47-49 (1939). [CW 155-157].

[12] "Instantaneous Emission of Fast Neutrons in the Interaction of Slow Neutrons with Uranium," L. Szilard and W.H. Zinn, P*hys. Rev.*55:799-800 (1939) (Letter). [CW 158-159].

“Divergent Chain Reaction in Systems Composed of Uranium and Carbon.”[13] In this long paper, Szilard identifies the design criteria for a reactor consisting of a large “sphere” of carbon in which is imbedded small spheres of uranium or even uranium oxide. This paper followed correspondence of early-July 1939 with Fermi who was at Ann Arbor for the summer, in which Szilard advanced the cause of graphite as moderator over that of water, and of configuring uranium in the form of lumps rather than sheets. Both recognized that a homogeneous mixture of uranium and moderator would lose too many neutrons to resonance absorption in uranium to work as a reactor.

The purpose envisaged for the reactor was to produce heat, for instance to power submarines. At that time the only route to a nuclear explosive was thought to lie in the isotopic separation of U^{235}, present in the amount of 0.71% in natural uranium.

> Soon after his February 1940 manuscript, Szilard received a May 1940 letter from Louis A. Turner, a theoretical physicist at Princeton, suggesting that U^{239} after two beta-decays forms $[94]^{239}$ which is likely as fissile as U^{235}. This was a bombshell to Szilard and was the first inkling of the possibility of plutonium weapons, the utility of a natural-uranium reactor in which the loss of neutrons to resonance absorption in U^{238} was not simply an impediment to criticality but the potential source of useful plutonium, and ultimately (to Szilard’s fertile mind) to the possibility of a uranium-plutonium breeding cycle that could convert most of (fertile) natural uranium to useful heat.

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[13] “Divergent Chain Reactions in Systems Composed of Uranium and Carbon,” Submitted to The Physical Review, February 1940, but publication withheld at the author’s request. *Report A-55,* the Uranium Committee, declassified in November 1946 as *MDDC-446* (1940), with additions and revisions. [CW 216-256].

The critical radius of the reactor is sensitive to the thermal neutron absorption cross section of graphite and its density. For a cross section of 0.01 barn and graphite density 1.7 g/cc, about 100 metric tons of graphite is required and about 30 tons of uranium. As Szilard noted in a speech of 1946[14]

"I felt that even if a chain reaction could be maintained in a uranium-water mixture, we would have to deal with very disagreeable chemical processes in such a system, if we attempted to use it for the liberation of atomic energy on a large scale. The radiations emitted from uranium would decompose water into hydrogen and oxygen and this explosive gas mixture would have to be removed."

In reality, both heavy-water and light-water reactors work all over the world, some of them with catalytic recombiners

Once the uranium-carbon reactor approach was accepted, Szilard in large part left the details to others. He was not only instigator but chief troubleshooter for the project at Columbia and Chicago. Without details to occupy him and knowing his own limitations as an experimenter, Szilard pushed himself to invent the fast-neutron breeder reactor[15] in which he found an application for the electromagnetic pumping of molten metal coolant—sodium, lead, or bismuth.

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[14] " *Creative Intelligence and Society: The Case of Atomic Research, The Background in Fundamental Science,"* [Public Lecture by Leo Szilard, University of Chicago, July 31, 1946] [WL 187]

[15] "Liquid Metal Cooled Fast Neutron Breeder," *Report MUC-LS-60* (March 6, 1945). [CW 369-375]

Szilard's engineering background, his willingness to talk to anyone to learn of problems and to anyone else to learn of potential solutions is well illustrated in a three-page document[16] important both from the point of view of building reactors and of nuclear explosives. Uranium powder had been produced by a calcium hydride reduction process, but it proved impossible to fuse into a solid. Furthermore, some batches of uranium powder were pyrophoric, bursting into flame spontaneously as soon as the lid of the can was removed. Others were not.

"Upon making inquiries," Szilard learned that it's customary to protect tungsten powder from surface oxidation by coating it with a thin layer of paraffin. He worked with F.T. Alexander who had prepared the uranium powder and had been unsuccessful in fusing it. Now they pressed paraffin-coated uranium powder in a die, heated it gently in a vacuum furnace to evaporate the paraffin and achieved a fused uranium ingot with a density exceeding 18 g/cc.

Looking forward to the reactor

Szilard published a memorandum[17] evaluating liquid bismuth, helium, hydrogen and air coolants. He envisioned at a power plant producing a nominal 300 MWt ("t" referring to "thermal" output), compared with the Hanford plant initially built at 200MWt.

Looking still further ahead, on July 14, 1942[18] Szilard returned to his work of the 1920s to scope the question of electromagnetic pumping for a bismuth-cooled production reactor. This was then expanded with a paper of November 23, 1942, about a week before the successful

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[16] "Preliminary Report on the Melting of Uranium Powder," by L. Szilard, August 16, 1941 (Report A-24). [CW 329-331].

[17] "On the Cooling of the Power Plant," by L. Szilard, June 15, 1942. [CW 332-345].

[18] "A Magnetic Pump for Liquid Bismuth," by D. Feld and L. Szilard, July 14, 1942. [CW 351-358].

operation of the Fermi pile[19]. He estimated that such a unit would produce about a kilogram per day of Pu-239.

The fast neutron breeder

I would love to go on for another hour about the fast breeder reactor, its potential for humanity, and why the right combination has not yet been demonstrated to have it dominate energy production for centralized grids, at least. But I want to use the few minutes remaining to mention Leo Szilard's pioneering work in information theory and then to comment on Szilard's acceptance by his peers. I leave it to Matt Meselson to discuss Szilard's work in biology and his initiative and dedication to arms control and the prevention of nuclear war.

Szilard in Information

Szilard's 1929 paper, "On the Decrease of Entropy in a Thermodynamic System by the Intervention of Intelligent Beings," aroused a (delayed) maelstrom of controversy. This is well treated in "Maxwell's Demon 2, Entropy, Classical and Quantum Information, Computing" edited by Harvey S. Leff and Andrew F. Rex (2003)[20]. I cannot in a few minutes resolve or even summarize the controversy aroused by Szilard in his explanation that Maxwell could not violate the second law of thermodynamics by action of a "demon" to identify, on the fly, gas molecules of speed higher or lower than normal and allow them to pass through a trapdoor. A firm understanding in this field has been provided by Rolf Landauer, Charles Bennett, and,

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[19] "Short Memorandum on Bismuth Cooled Power Unit," by L. Szilard, November 23, 1942. [CW 359-368].

[20] Henceforth cted as [MD2].

separately, by Oliver Penrose, with clear explanations by Leff and Rex themselves. The resolution of the paradox is ascribed to the entropy increase associated with the *erasing* of the information in a memory, analog or digital.

Rather than consider in detail the classical Maxwell demon, Szilard in 1929 invented several of his own. In his first example, a cylindrical space containing a single molecule was divided in two by a frictionless and weight-balanced piston. The experimenter noted on which side of the piston the molecule found itself and moved the piston slowly away, thus allowing the “gas” to expand to double its volume, absorbing heat from the walls in contact with a thermal reservoir. The piston is then removed (or tilted or valved) and reinserted to again divide the cylinder in two; determining in which half the molecule resides permits the experimenter to move the piston again away from the molecule, extracting work at the expense of heat input, but with no heat rejection[21].

For those discomfited by a gas consisting of a single molecule, Szilard considered a totally different approach in which a finite cylinder contained a mixture of two gases and two semi-permeable pistons or movable membranes as well as two opaque pistons.

Key to his invention were atoms or molecules that could change their identity so that a piston that had been impermeable 0becomes transparent to that particular species.

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[21] The piston can be arranged to move only in a single direction, if it is removed and then reinserted when the molecule was found to be below rather than above the piston.

As noted by Lanouette in his presentation, such an approach is now used for practical purposes of cooling and compressing groups of atoms or molecules[22]. These utilize conveniently manipulable spin orientations that can be converted from one to another by "adiabatic rapid passage" of near-resonant laser beams[23,24].

In his pioneering paper of 1929, Szilard demonstrated remarkable insight, originality, and ingenuity.

Szilard and his peers

Referring probably to Szilard's dropping in on him at Columbia University around 1935, I.I. Rabi is quoted by Lanouette [WL-155],

> *"Szilard kept telling me which experiments I should conduct. … Finally, I said, 'Leo, if you really think this is so important, do it yourself.' Of course he never did."*

In the construction of the exponential piles in Pupin Hall at Columbia University, all pitched in to pile the graphite bricks, except Szilard, who hired a husky undergraduate to do the work for him. Ever the first to lead his team by actually doing things himself, Fermi was disconcerted by this initiative. Eventually, George Pegram, Dean at Columbia, saw the merit of Szilard's approach and pressed the Columbia football team into service.

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[22] Mark Raizen and his group at University of Texas, Austin. http://george.ph.utexas.edu/research.html

[23] An implementation of E. Lubkin's suggestion to "…apply a causal Hamiltonian motion to rotate that [lower level] to the upper level." [MD2-198]

[24] See the work of Mark G. Raizen's group at the University of Texas, Austin, at http://george.ph.utexas.edu/research.html

Nina Byers recalls[25] that Szilard and Fermi were not on speaking terms when she was a graduate student at Chicago, 1950-1956, and in fact she was invited by Szilard to report on the substance of lectures Fermi was giving on isotopic spin and pion physics. In her interesting and accessible memoir, Byers quotes Szilard,

> *"Fermi is a scientist pure and simple. This position is unassailable because it is all of one piece. I doubt he understood some people live in two worlds like I do. A world, and science is a part of this one, in which we have to predict what is going to happen, and another world in which we try to forget these predictions in order to be able to fight for what we would want to happen."*

Finally, Ted Puck in Szilard's days as a biologist, explained in a December 1955 letter to Leo why Puck would not offer him a position in his lab[26],

> *"…in December 1955, Puck admitted that no permanent post would be offered in Denver. 'With the greatest possible reluctance I have come to the conclusion that it is not possible for me personally to work with you scientifically,' he wrote Szilard. 'Your mind is so much more powerful than mine that I find it impossible when I am with you to resist the tremendous polarizing forces of your ideas and outlook.' Puck feared his 'own flow of ideas would slow up & productivity suffer if we were to become continuously associated working in the same place and the same general kind of field.' Puck said, 'There is no living scientist whose intellect I respect more. But your tremendous intellectual force is a strain on a limited person like myself.'"*

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[25] "Fermi and Szilard," by Nina Byers. In *Fermi Remembered*, J.W. Cronin, Ed., 2004. Available *arXiv:physics/0207094v3*

[26] [WL-406]

Szilard recognized early that he had far too many ideas to work them all out himself. His batting average was high, but even superior mortals such as Fermi and Rabi found their approach to science threatened by Szilard's insightful suggestions. They valued thoroughness and completion of what they started.

On the other hand, we have Robert Browning's view,

> *"Ah, but a man's reach should exceed his grasp,*
> *Or what's a heaven for?"*

Szilard strived to help mankind in general, and he also cared deeply for individuals. Though dismayed with Edward Teller's 1954 testimony in the Oppenheimer affair, and letting Teller know it, he still intervened to obtain the release of Teller's mother and sister from Hungary.

I think that Leo Szilard was happy and cheerful, despite his self-assigned mission to reform the world. I close with his comment,[27] characteristic of his views,
"With this remark of Turner [May, 1940] a whole landscape of the future of atomic energy arose before our eyes in the Spring of 1940 and from then on the struggle with ideas ceased and the struggle with the inertia of Man began."

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[27] " *Creative Intelligence and Society: The Case of Atomic Research, The Background in Fundamental Science,"* [Public Lecture by Leo Szilard, University of Chicago, July 31, 1946] [WL 178-189]