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Physics in Perspective

John von Neumann and Klaus Fuchs: an Unlikely Collaboration

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I discuss the origin of the idea of making a fusion (hydrogen) bomb and the physics involved in it, and then turn to the design proposed for one by the unlikely collaborators John von Neumann and Klaus Fuchs in a patent application they filed at Los Alamos in May 1946, which Fuchs passed on to the Russians in March 1948, and which with substantial modifications was tested on the island of Eberiru on the Eniwetok atoll in the South Pacific on May 8, 1951. This test showed that the fusion of deuterium and tritium nuclei could be ignited, but that the ignition would not propagate because the heat produced was rapidly radiated away. Meanwhile, Stanislaw Ulam and C.J. Everett had shown that Edward Teller's Classical Super could not work, and at the end of December 1950, Ulam had conceived the idea of super compression, using the energy of a fission bomb to compress the fusion fuel to such a high density that it would be opaque to the radiation produced. Once Teller understood this, he invented a greatly improved, new method of compression using radiation, which then became the heart of the Ulam–Teller bomb design, which was tested, also in the South Pacific, on November 1, 1952. The Russians have freely acknowledged that Fuchs gave them the fission bomb, but they have insisted that no one gave them the fusion bomb, which grew out of design involving a fission bomb surrounded by alternating layers of fusion and fission fuels, and which they tested on November 22, 1955. Part of the irony of this story is that neither the American nor the Russian hydrogen-bomb programs made any use of the brilliant design that von Neumann and Fuchs had conceived as early as 1946, which could have changed the entire course of development of both programs.

Key words: John von Neumann; Klaus Fuchs; Stanislaw Ulam; Edward Teller; nuclear fission; nuclear fusion; von Neumann–Fuchs hydrogen-bomb design; Ulam–Teller hydrogen-bomb design; Russian hydrogen-bomb design; atomic espionage.

Introduction

After the death of the mathematician John von Neumann in 1957, *Life* magazine revealed that in a 1950 interview he had told an interviewer, “If you say why not bomb them [the Russians] tomorrow I say why not bomb them today? If you say today at five o'clock, I say why not one o'clock?”[1] That same year the German-

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born British theoretical physicist Klaus Fuchs was arrested in England and confessed to having been a spy for the Soviet Union. I do not know if von Neumann knew this when he made his statement. If so, he may have recalled that in the spring of 1946 when they were both at Los Alamos, he and Fuchs applied for a patent for a version of the hydrogen bomb, which after substantial modification was actually tested on May 8, 1951. This test, known as "Greenhouse George," was done on the island of Eberiru on the Eniwetok atoll in the South Pacific. It was the largest nuclear explosion ever done up to that time. Its yield was some ten times greater than the bomb that destroyed Nagasaki on August 9, 1945. Many of the details of the design of that bomb had been given to the Russians by Fuchs earlier in 1945 and certainly speeded up their development by years. What I want to explain here is that, while Fuchs turned over the details of his patent with von Neumann to the Russians in March of 1948, this work seems to have had no effect on their program. It had no explicit affect on the American program either, which is nearly as much of a paradox as the Fuchs–von Neumann collaboration itself. The device tested at Greenhouse George was almost an afterthought. By this time the real hydrogen bomb had been invented by the Polish-born mathematician Stanislaw Ulam and Edward Teller. It was tested on November 1, 1952, also in the South Pacific, and produced a yield about a hundred times greater than Greenhouse George. To understand all of this I need to give a brief history of the development of the hydrogen bomb.

The Initial Idea: Fermi, Teller, and Bethe

As far as I can tell, the first discussion of how to design a thermonuclear device, a hydrogen bomb, took place in September of 1941 at Columbia University where Enrico Fermi was then a professor and Edward Teller was working on the Manhattan project that was exploring the possibilities of nuclear weapons. As Teller later recalled:

> It [the hydrogen bomb] started at Columbia, and in this case it was an idea of Enrico Fermi that triggered it. We usually had lunch in the faculty club and as we came back from lunch to Pupin [where the physics department was located] I remember that Fermi stopped just before Pupin and said, "Now if the nuclear bomb works we can reproduce fusion… the energy source in the Sun, except of course we would not use hydrogen but deuterium where the cross-section [which determines the rate of the reactions] is very much bigger." I gave it some thought and practically a week later [on another walk] I proved to Fermi that it was a bum idea.[2]

Teller then moved to Chicago but was still obsessed by Fermi's idea, which he could not quite convince himself was wrong.

The next development came in the summer of 1942 in the compartment of a train that Hans Bethe shared with Teller. They were on their way to San Francisco to attend a meeting that had been organized by Robert Oppenheimer to study the design of atomic weapons. Los Alamos was not created until the following spring. Bethe was then a professor at Cornell while Teller was at the University of Chicago. So Bethe stopped off in Chicago to pick up Teller and to get a look at the reactor Fermi and his group were then constructing. After having seen their work, Bethe became convinced that the reactor would work and that a nuclear weapon would also probably work. In an interview I had with Bethe many years ago this is what he told me.

> We had a compartment on the train to California, so we could talk freely. Teller told me about the idea of making plutonium in the reactor and using the plutonium in a nuclear weapon….
>
> Teller told me that the fission bomb [the Hiroshima and Nagasaki bombs were fission bombs] was all well and good and, essentially, was now a sure thing. In reality, the work had hardly begun. Teller likes to jump to conclusions. He said that what we really should think about was the possibility of igniting deuterium by a fission weapon—the hydrogen bomb. Well, the whole thing was far more difficult than we thought then. About three-quarters of our time that summer was occupied with thinking about the possibility of a hydrogen super-weapon. We encountered one difficulty after another, and came up with one solution after another—but the difficulties were clearly in the majority. My wife knew vaguely what we were talking about, and on a walk in the mountains in Yosemite National Park she asked me to consider carefully whether I really wanted to continue to work on this. Finally, I decided to do it. It was clear that the super bomb, especially, was a terrible thing. But the fission bomb had to be done, because the Germans were presumably doing it.[3]

To understand the “difficulties” and how the von Neumann–Fuchs invention addressed some of them I need to review a bit of the physics of nuclear weapons.

Fission and Fusion

In principle, nuclear weapons are of two types: fission and fusion. In practice, most weapons are a mixture. Fission weapons, like the ones that destroyed Hiroshima and Nagasaki, derive their energy from the process of nuclear fission. This happens when a heavy nucleus like one of the isotopes of uranium or plutonium breaks up into a pair of lighter elements. This can happen spontaneously or it can be induced when the parent nucleus absorbs an ambient neutron. When this happens, a “compound nucleus” is formed, generally in a state of high excitation. This excitation causes the compound nucleus, which can be thought of as analogous to a liquid drop, to vibrate very rapidly and ultimately break up into fission fragments, which are nuclei somewhere in the middle of the periodic table. For example, the first fission of uranium, which was observed at the end of 1938 by the German chemists Otto Hahn and Fritz Strassmann, was into barium and krypton. These fission fragments are generally what are known as "neutron rich." Their nuclei contain more neutrons than protons. To move toward stability, where the number of neutrons and protons approach equality, the fragments almost immediately shed neutrons—on average something like three. These neutrons can cause other nuclei to fission, creating a chain reaction. When enough materiel is present, this chain reaction can run away in microseconds, producing an explosion. There is energy created in fission because the final products are less massive than their parents. The mass difference produces energy according to Einstein's formula $E = mc^2$. This energy is carried off primarily as kinetic energy of the fission fragments.

While fission involves heavy elements such as uranium or plutonium, fusion involves light elements such as the isotopes of hydrogen. There are three: the nucleus of ordinary hydrogen consists of one proton, the nucleus of "heavy" hydrogen—the deuteron—consists of one proton and one neutron, while the nucleus of "super-heavy" hydrogen—the triton—consists of two neutrons and one proton. I shall follow the usual notation and call the proton p, the deuteron D, and the triton T. A typical and very important fusion reaction occurs when two deuterons fuse to produce one triton and one proton. Symbolically, we can write this as $\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T} + \mathrm{p}$. This generates energy because the triton and the proton have less mass than the two deuterons. This mass-energy is largely taken off by the kinetic energy of the proton. The first difficulty we have to deal with is that according to classical physics this interaction is impossible.

The reason is that each deuteron carries a positive electric charge and like charges repel. These like charges set up a barrier that classical physics tells us cannot be penetrated. It would violate the conservation of energy. But in quantum mechanics, energy conservation can be violated if it happens in a sufficiently short time. This is one of Heisenberg's uncertainty relations. Therefore, there is a probability that the two deuterons can penetrate the barrier. Once they do, the strong nuclear force takes over and the fusion reaction is completed. We know that this sort of fusion produces the energy in the Sun and the other stars. The reactions are different there but are the same principle. It works for the Sun because its very high central temperature—millions of degrees—corresponds to very energetic nuclei, which aids the fusion. So to make deuterium "ignite," to fuse, you need to produce temperatures like that of the Sun. Such temperatures are produced by an atomic bomb. This is what Bethe was referring to.

The Hydrogen Bomb

The first question we want to answer is why are fusion bombs so powerful as compared to fission bombs. The most energetic fusion reaction known involving hydrogen isotopes is the fusing of a deuteron and a triton to produce a stable isotope of helium plus a neutron. Symbolically, $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He}^4 + n$. The superscript 4 indicates that this isotope of helium has two neutrons and two protons in its nucleus. This reaction generates something like a tenth of the energy of a typical fission reaction. Hence the puzzle. The answer is that the mass of the deuteron and triton is about a 50th of the mass of, say, uranium. Hence, a gram of uranium contains about a 50th of the atoms compared to a gram of deuterons and tritons. This compensates for the difference in energy. You get more energy per gram in fusion than you get in fission because there are more nuclei. To put the matter more specifically, if you were to fission 1 kilogram (kg) of uranium it would produce an energy equivalent to 20,000 tons of TNT, but if you were to fuse 1 kg of D and T it would produce an energy equivalent to about 80,000 tons of TNT.

I have to confess that when I interviewed Bethe on his work on the early versions of the hydrogen bomb—the "Classical Super" as it was called—I knew next to nothing about the physics of nuclear weapons. This was even though I had spent the summer of 1957 as an intern at Los Alamos, and had witnessed two nuclear explosions in the desert in Nevada. There was a strict "need to know" at Los Alamos, and since I was not working on weapons no one told me anything. When Bethe told me about the idea of "igniting deuterium" with a fission bomb the image I had was of dropping a lighted match in a container of gasoline. The image I should have had was trying to ignite a log with a match. I probably would be able to ignite a small patch of the log near the match, but then it would cool off before the fire could propagate throughout the log. This is what calculations showed would happen with the Classical Super. The heat of the fission bomb would ionize whatever atoms were around, meaning that atomic electrons would be torn off. When these electrons interacted with the nuclei they would become accelerated, which produces radiation that leaks out and cools off the configuration. In short, the fission bomb might ignite the deuterium but this ignition would not propagate. Teller proposed one configuration after another and none of them seemed to work. I.I. Rabi, who was a witness to all of these, told me that Teller reminded him of a man who used to come and see him about a perpetual-motion machine he had invented. Rabi would patiently explain to him why it could not work. The man would thank him and in a few days come back with the design of a new perpetual-motion machine.

In the late summer of 1945, Fermi gave lectures at Los Alamos on the Classical Super. He had a gift for going to the essence of everything and presenting the results in the simplest terms possible. Fermi discussed how fusion is produced in the Classical Super and how the energy is lost. At the end he summed up by saying that, "So far all schemes for initiation of the super are rather vague." This I think was being polite. Fuchs was at the lectures, and he turned his notes over to the Russians. They were translated into Russian and in January of 1946 presented to a special committee of experts presided over by Lavrentii P. Beria who had been put in charge by Stalin of the Russian bomb program.* Probably the most important

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*I am grateful to German A. Goncharov for this information and for other details concerning the Russian program.

Fig. 1. John von Neumann (1903–1957). Credit: American Institute of Physics Emilio Segrè Visual Archives.

thing they learned was that the Americans were working on the hydrogen bomb and considering the fusion of deuterium and tritium. But in April of 1946 Teller organized a three-day conference and Fuchs and von Neumann attempted to explain to some people at the conference what their new idea was. No one seemed to be interested. One thing that interests me is how this unlikely pair ever collaborated in the first place.

Von Neumann and Fuchs

Neumann János Lajos, using the Hungarian name order, was born in Budapest in 1903. His father was a non-practicing Jewish lawyer who worked for a bank. It was evident from the beginning that the young von Neumann—the "von" had been awarded to his father—was a prodigy. His father was concerned that the practice of mathematics might not be a practical way of earning a living, so at the age of 22 von Neumann took PhDs in both mathematics and chemical engineering. After his father's death in 1929 the von Neumanns moved to the United States. Such was his mathematical reputation that he became one of the first faculty members, joining Albert Einstein, at the newly created Institute for Advanced Study in Princeton. He spent the rest of his career there. Von Neumann (figure 1) was a very social individual. He loved parties, food and drink and ribald limericks. Einstein referred to him somewhat disdainfully as a *Denktier*—a think animal. With the war he became a consultant at Los Alamos where his chemical engineering background came in

Fig. 2. Klaus Fuchs (1911–1988) at age 22 in 1933. Source: Emil Fuchs, *Mein Leben.* Part 2 (Leipzig: Koehler & Amelang, 1959), facing page 224.

handy. He helped to design the explosive lenses that were used to implode the sphere of plutonium used in the Nagasaki bomb. One of the things he did after the war was to create the logical architecture of the computer. When I was an undergraduate at Harvard he came to the university to give lectures on the computer and the brain. They were the best lectures I have ever heard on anything—like mental champagne. After one of them I found myself walking in Harvard Square and looked up to see von Neumann. Thinking, correctly as it happened, that it would be the only chance I would have to ask him a question, I asked, “Professor von Neumann, will the computer ever replace the human mathematician?” He studied me and then responded, “Sonny, don’t worry about it.”

Klaus Emil Julius Fuchs, the third of four children of a Lutheran pastor, was born in 1911 in Rüsselsheim, Germany. He became a member of the German Communist Party in 1932 when he was a student at the University of Kiel (figure 2). When the Nazis took over it was clear that his life was in danger so he emigrated first to France and then to England where in 1936 he took his Ph.D. degree at the University of Bristol. It was there that he first met Bethe who had also left Germany. Fuchs then went on to Edinburgh to work with the noted German refugee physicist Max Born. When the war broke out, Fuchs was interned as an enemy alien and sent to Canada where he used some of his time to give instructive physics lectures to some of his fellow internees. But Born managed to get him released so he could return to England. By this time Rudolf (later Sir

Rudolf) Peierls was working on nuclear weapons. He invited Fuchs to join him at the University of Birmingham where he was then teaching. The Peierlses often boarded physicists in their home. Bethe had lived with them for awhile and now they boarded Fuchs. As I can testify from personal experience, Peierls's Russian-born wife Genia was a force of nature. Fuchs was a mystery to her. He did not say anything unless asked a direct question. He reminded her of one of those machines that played music only when you put a coin in.

Fuchs and Peierls did some important work together. For example, they wrote a fundamental paper on the theory of isotope separation.[4] To use uranium for a bomb you must separate the two isotopes uranium-235 and uranium-238 and they discussed, among other things, how to use centrifuges for this purpose. Some of the British group were invited to come to the United States to continue their work. When Fuchs received such an invitation he attempted to decline it on the grounds that what he was doing in England was more important. When the Germans invaded Russia, Fuchs decided that it was necessary for the Russians to get the bomb so he began transmitting information. He certainly must have transmitted the work he had done with Peierls. His British spy connections were well established and he did not want to lose them. In the event, Fuchs agreed to come to the United States and in August of 1944 he was at Los Alamos as a member of the Theoretical Division of which Bethe was the head. At Los Alamos he was very well liked. Since he was non-social he volunteered to act as a baby sitter for his more sociable colleagues who wanted to attend the many parties. He was extremely competent and had an almost photographic memory. Next to Oppenheimer he may have known more about all the activities of the laboratory than anyone. He was constantly transmitting this information to the Russians. In June of 1946 he returned to England where he was appointed as Head of the Theoretical Physics Division of the recently created British Atomic Energy Research Establishment. For awhile he stopped his espionage activities but in 1947 he presented himself to the Russian embassy. This kind of self-recruitment is not how spies were supposed to operate, so at first the Russians were suspicious. But they decided that he was sincere and gave him as a control Alexander S. Feklisov, a master spy who had handled the Rosenbergs. When Feklisov offered Fuchs money, Fuchs was outraged. He only took money in 1949, the last year of his espionage activity, when a brother contracted tuberculosis and sought treatment in an expensive clinic in Switzerland.

The von Neumann-Fuchs Design

Given this background, one can appreciate how strange the Fuchs–von Neumann collaboration was. Who started it and who contributed what? There are very few clues. An interesting one is the patent application, "One proposed design for the 'Super'," which was filed at Los Alamos in May of 1946.* The version I have is

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*I am grateful to Carey Sublette for this document.

essentially totally redacted. The proposed claim reads: "The combination with a device for initiating a thermo-nuclear reaction which employs a quantity of fissile material adaptable to sustain a neutron-induced divergent chain reaction, a massive quantity of material in which a thermo-nuclear reaction be maintained." It carries essentially zero information. But the significant thing is that von Neumann is given as the first author. This presumably means that he instigated the collaboration. A second clue comes from an FBI report by an agent, Robert Lamphere, who interviewed Fuchs in jail in England in 1950. Lamphere was not a physicist so he did not question Fuchs in as much detail as he might have. In any event, the FBI was more interested in Fuchs's contacts than in what he actually transmitted. To understand Lamphere's question and Fuchs's answer I need to say something more about the physics.

Fusion is what is known as a "binary" process. This means that the fusing nuclei react in pairs. What this implies is that the rate of the reaction is proportional to the product of the number of each of the fusing nuclei in a unit volume. If the two fusing nuclei are identical as in a D–D fusion this product is the square of the number densities. How can we increase this density? We can shrink the volume. We will then have the same number of particles but in a smaller volume, so the density is correspondingly higher. From this it follows that to increase the fusion rate one method is to compress the volume in which the fusing particles are contained. In the D–D case, if you compress the volume by a factor of ten the rate increases by a factor of 100. When Lamphere asked Fuchs who thought of this, Fuchs said that he did. "[Fuchs] stated laughingly that this was his, Fuchs', suggestion, and that he did not furnish information concerning the ignition of the super bomb by the implosion process."[5] The last part of this quote is quite incomprehensible to me because what Fuchs did was to turn over precisely this information. What role von Neumann played in the invention is not clear. To understand what Fuchs turned over I call your attention to the diagram in figure 3, which first appeared in Greg Herken's book *Brotherhood of the Bomb*.[6] He thanks Joeseph Albright and Marcia Kunstel, who were correspondents in Moscow where they acquired it. The version in Herken's book has Russian captions that presumably are translations of Fuchs's captions. Carey Sublette, who supplied this version, had the captions retranslated into English.

The box stands for a fission device. Von Neumann and Fuchs specified a gun-assembly weapon of the kind that flattened Hiroshima. It consists of a target made of highly enriched uranium and a projectile also made of highly enriched uranium. When the target is joined with the projectile by firing one against the other a supercritical mass is formed and the explosive chain reaction follows. But the momentum of the projectile acts as a ram that produces the first compression of the capsule, made in this instance from beryllium oxide. The capsule contains the D–T mixture, here in liquid form. The larger of the two spheres shown in the diagram represents this brute-force mechanical compression. It is probably optimistic to imagine such a perfect geometrical shape resulting from such a collision.

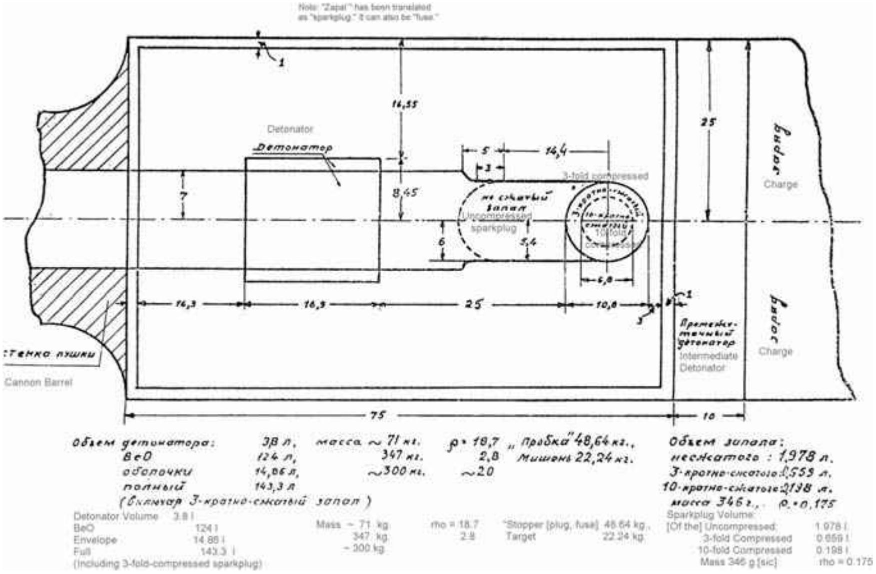

Fig. 3. The design for thermonuclear ignition that Klaus Fuchs turned over to his Soviet control in March 1948. The detonator (*box*) on the *left* represents a gun-type fission bomb consisting of a projectile and target of highly enriched uranium (71 kg of 70% pure U^{235}), which when joined form a supercritical mass and produce an explosive chain reaction. The projectile is carried forward by its momentum, striking the beryllium-oxide (BeO) capsule on the *right*, which contains a liquid 50:50 D–T mixture, compressing it by a factor of about 3, as represented by the *outer circle*. The radiation produced in the fission bomb heats up the BeO capsule, producing completely ionized BeO gas, which exerts pressure on the completely ionized D–T gas, compressing the capsule further to an overall factor of about 10, as represented by the *inner circle*. I thank Allen Thomsen for translating the Russian specifications into English and Carey Sublette for preparing this diagram.

In the diagram this is supposed to result in an increase in the D–T density by a factor of three.

There is no ingenuity here—only brute force. It is the next step that is ingenious. The initial radiant energy from a nuclear explosion is given off largely in X-rays. This radiation moves with the speed of light, which means that if you can make use of it you can speed up the next stage of the explosion where the real compression is supposed to occur. It has been known for over a century that the radiation itself produces a pressure. But this is much too small to cause the compression we are interested in. But the radiation, when it is suitably directed, heats up the beryllium-oxide container and its contents to a point where all of the electrons in the atoms are liberated. In short, the matter is completely ionized. In the von Neumann–Fuchs scheme the beryllium-oxide gas and the D–T gas (it is a gas because the heat has vaporized everything) are at the same temperature. Now, we can count up the number of particles that have been liberated per atom. Oxygen gives up eight electrons and beryllium four, so counting the two nuclei there are 14 particles. The hydrogen isotopes each give up one electron and then there are the two nuclei to make a total of four. So the ratio of the number of particles in the two gases is something like three to one. But when gases are in equilibrium at a common temperature this is also the ratio of the pressures. The beryllium-oxide gas exerts a pressure on the D–T gas, which accounts for the second compression. This is now known as "ionization compression," a descriptive term that was introduced by the Russian physicist and historian German Goncharov, who worked with Andrei Sakharov, who invented the same method independently. Goncharov has informed me that the Russian physicists referred to it as "sakharization," a pun on the Russian word for "sweetened."* In the example of the above diagram the overall compression is by a factor of about ten. The notions conveyed in the diagram were tested in the Greenhouse George explosion although that device was very substantially modified from the original von Neumann–Fuchs design. People who were present at the time never heard this design mentioned.** Von Neumann was a consultant and he must have had something like this in mind although given Fuchs's outing he might well have been reluctant to bring up the name of his former collaborator. A completely different form of radiation compression is used in the Ulam–Teller hydrogen bomb, which bears no real resemblance to the von Neumann–Fuchs design. I will come back to this below.

The Ulam–Teller Design

While the Greenhouse George test showed that the Fuchs–von Neumann design would ignite the fusible D–T, once ignited the reaction still would not propagate. An equilibrium condition had been established after the ignition and the heat that was produced was radiated away very rapidly. In short, everyone was stuck. No one knew how to make a hydrogen bomb. Enter Stanislaw Ulam (figure 4). Ulam was born in 1909 in Lwow, which after the First World War became part of Poland. Like many mathematicians his abilities manifested themselves early. Indeed, in 1938 he was invited to become a Junior Fellow at Harvard. Arthur Schlesinger, Jr., was a Junior Fellow at the same time. But in 1939 he returned to Poland escaping with his brother Adam just before the war. The rest of his family perished in the Holocaust. Adam eventually became a professor of government at Harvard and Ulam became a professor at the University of Wisconsin. Not long after Los Alamos was founded, von Neumann, whom Ulam had happened to know in 1935 when he was a visitor at the Institute for Advanced Study, recruited Ulam for work

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*I thank Norman Dombey for pointing this out. "Sakhar" is the Russian word for "sugar."

**I thank Kenneth Ford, Arnold Kramish, and Herbert York, who were present, for their comments.

Fig. 4. Stanislaw Ulam (1909–1984). Credit: American Institute of Physics Emilio Segrè Visual Archives.

on a project, the atomic bomb, which von Neumann was not allowed to say anything about beyond that it was interesting and important. Ulam was instructed to proceed to a railway stop near Santa Fe. He sent his wife Françoise to the library to take out an atlas of New Mexico. When he looked at the list of recent borrowers he noticed that they were physicists who had disappeared from the department.

It is often the case in my experience that when you ask a mathematician about some problem you cannot solve, he/she shows that it is equivalent to another problem that he/she also cannot solve. Ulam was not like that. He solved problems. One of the things he did during the war was to invent the so-called Monte Carlo method, which is used for making approximate analyses of problems that cannot be solved exactly. After the war Ulam decided to stay at Los Alamos. It was inevitable, especially after President Truman's decision, that he would turn his attention to the hydrogen bomb. In 1950, he and a younger colleague, C.J. Everett, decided that they would make an independent analysis of the Classical Super. By June they had concluded that the situation was more hopeless than anyone had imagined. But the exercise gave Ulam a greater mastery of the physics than anyone else had.

Here things stood until December when Ulam had a brainstorm. It goes under the rubric "super compression." Suppose you could use the energy of the primary fission bomb directly to compress the fusion fuel.* Hypothetically, there would be enough energy to compress the fuel not to the factor of ten in the von Neumann–

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*It is likely that Ulam first wanted to apply super compression to an ordinary fission bomb to improve its efficiency. But then he realized how it was relevant to the Super.

Fig. 5. Edward Teller (1908–2003). Credit: American Institute of Physics Emilio Segrè Visual Archives.

Fuchs scenario but to, say, a factor of eighty. This could compress the fuel—for example, deuterium—and everything surrounding it to such a high density that it would become opaque to the radiation being produced in the interior. It would act like a sort of shroud. It would not matter if equilibrium was reached because the radiation would be contained in the interior and would not cool the fusible elements. Ulam's idea was to produce this compression using the detritus from the primary fission device—the neutrons and the fission fragments. In late January, he went with this scheme to Carson Mark, a Canadian who had come to Los Alamos during the war and had stayed on to become Head of the Theoretical Physics Division. Mark was busy with Greenhouse George and after listening for an hour told Ulam to talk to Teller. Having known Ulam, who died in 1984, I imagine that Mark must have heard any number of Ulam's fanciful speculations of which he had at least one a day. It should also be noted that at the time there was no nuclear device that was small enough—a "bomb in a box"—to be used this way.*

Ulam and Teller did not like each other, to put it mildly. Both men had outsized egos and it could not have helped that Ulam had recently shown that for all practical purposes, Teller's Classical Super was dead. That apart, Teller (figure 5) had a "theorem" that had persuaded him that no amount of compression, super or otherwise, could help. Teller of course understood that when you compress the

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*Ken Ford has informed me that he had an interview with Carson Mark who made this point. A slightly redacted written version of this interview has been produced.

fusible elements this increases the reaction rate of the fusions. But he argued that the rates of all the processes by which energy is dissipated by radiation are increased by exactly the same amount—something that is known as "scaling." It turned out that he had left out a crucial process that did not have this property. You could indeed beat the system and compression would work.* Once Teller understood this he embraced the idea enthusiastically, so enthusiastically that in his later accounts he more or less claimed to have invented it. What he did invent was the method of compression using radiation, which was a vast improvement over what Ulam was proposing. This radiation compression is totally different from the von Neumann–Fuchs idea. Whether he had their proposal somewhere in the back of his mind, who can say. In any event, it worked, and we had, for better or worse, the Ulam–Teller hydrogen bomb.

The Russian Hydrogen Bomb

The Russians were alarmed by the Truman edict and began working furiously on their own hydrogen bomb. The first design they tested was not really a hydrogen bomb although it did involve fusion. They called it the *Sloyka*, a kind of Russian layer cake. In the center was a fission device that was surrounded by spherical shells, layers, of alternating fission and fusion fuels. When the primary was exploded this set off a sequence of secondary events involving both fission and fusion. At about the same time as the Americans they hit on the idea of super compression. Who exactly was responsible and how this came about I do not know. However, I am quite sure that it had nothing to do with espionage. The Russians have freely admitted that Fuchs gave them the fission bomb, but they have adamantly denied that anyone gave them the hydrogen bomb. German Goncharov, who was there, has informed me that the government minister who was then in charge of the program, Andrei Malyshev, opposed working on it in favor of the *Sloyka*. It was not until 1954 that he changed his mind. The Russians tested their first hydrogen bomb in 1955, the British in 1957, the Chinese in 1967, and the French in 1968.

On November 22, 1955, Goncharov witnessed the first Russian hydrogen-bomb test. On the 50th anniversary of this test, Goncharov published an article with the curious title "The extraordinarily beautiful physical principle of thermonuclear charge design."[7] In it he discusses the role of Fuchs as the Russians perceived it. He tells us that in September of 1945 Fuchs transmitted information about the Classical Super including a diagram that he presents in his article. The effect of this was to alert the Russians that the Americans were working on a hydrogen bomb

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*"Bremsstrahlung" ("braking radiation") is a process in which an electron that has been accelerated or decelerated by its interaction with a nucleus emits radiation. But there is inverse Bremsstrahlung in which a radiation quantum is absorbed by the electron. This process takes place when a nucleus is present, and hence there are three bodies involved, so Teller's theorem is evaded. This process contributes significantly to the opacity. I thank Carey Sublette and Ken Ford for comments on this.

and that they had better look into the matter. But the Russians, also using material supplied by Fuchs, were busy trying to duplicate the plutonium fission weapon. They made the first successful test of it in August of 1949. Meanwhile, Fuchs had delivered the von Neumann–Fuchs invention to his London contact, Alexander Feklisov. Goncharov informs us that this was immediately given to Beria. He called in two Russian physicists to analyze this new information. It is important to understand that only a miniscule number of Russian scientists were allowed to see any espionage data. Some of it was kept from people who really needed it. Why Beria took this position I do not know. One of the people who was allowed to see these reports was Yuri Khariton—a leader in the Russian program. He summarized the von Neumann—Fuchs invention without really understanding it. In fact, the Russians did not understand it until 1954 when Sakharov and others designed the real hydrogen bomb.

Part of the irony of this story is that the unlikely collaborators, John von Neumann and Klaus Fuchs, produced a brilliant invention in 1946 that could have changed the whole course of the development of the hydrogen bomb, but was not fully understood until after the bomb had been successfully made. However, it would have been better for everyone if it had never been made at all.

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