A memorandum that changed the world

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We present an analysis of both the content and the influence of the 1940 memoir by Otto Frisch and Rudolf Peierls that showed that nuclear weapons were possible.

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In the summer of 1939 Otto Frisch, who was in Copenhagen, received an invitation from Mark Oliphant, a professor of physics at Birmingham, to come to Birmingham for the summer to see if some arrangements might be made for Frisch to emigrate to Birmingham. War came that fall and Frisch could not return safely to Denmark. He was given a lectureship that enabled him to stay.

The previous Christmas he had gone to visit his aunt Lise Meitner in Kungalv in Sweden. She had just received a letter from Otto Hahn, the radiochemist in Berlin with whom she had collaborated for many years before she was forced to flee Germany. Meitner and Hahn had been using neutron sources to bombard various elements including uranium. Hahn had continued the experiments with Fritz Strassmann, another chemist. They had found something they did not understand. Instead of finding elements in the residual bombarded uranium that had masses comparable to uranium, they found barium, which was somewhere in the middle of the Periodic Table. They were stuck for an explanation and Hahn appealed to Meitner. She and Frisch went for an excursion in the snowy woods—he on skis and she on foot. During that outing they realized that by using the liquid drop model of the heavy nuclei, what Hahn and Strassmann had done was to fission the uranium nucleus. One product was barium and the other was krypton with possible neutrons in addition. They worked out the energies and realized that about 200 MeV would be released, a very large amount of energy compared to any chemical reaction.

Frisch returned to Copenhagen after this visit with his aunt (his aunt remained in Sweden) and told Bohr about what he and Meitner had concluded. Bohr's reaction was like a great many other physicists when they heard about it—it was so obvious why had not they thought of it. As it happened Bohr was about to leave for the United States where he was going to spend time at the Institute for Advanced Study which was then located at Princeton University. He was accompanied by his assistant Lèon Rosenfeld. On the Atlantic crossing Bohr had a blackboard setup in his cabin, and he and Rosenfeld went over the theory. He had promised Frisch and Meitner not to say anything until their paper appeared, but he had forgotten to tell Rosenfeld who went at once to Princeton and told everybody.

Even in those preinternet days the news spread all over the country and abroad and fission experiments proliferated. Among the first were those of Frisch, who was primarily an experimentalist. He looked for ionization pulses, which were produced by the charged fission fragments. Others found the additional neutrons—on average a little over two—produced in the fission process. Ironically, the barium-krypton split which Hahn and Strassmann found was a relatively unlikely nuclear splitting.

In his autobiography, *What Little I Remember*,[1] Frisch writes "In all this excitement we had missed the most important point. It was Christian Møller, a Danish colleague, who first suggested to me that the fission fragments (the two freshly formed nuclei) might contain enough surplus energy to each eject a neutron or two; each of these might cause another fission and generate more neutrons. By such a "chain reaction" the neutrons would multiply in uranium like rabbits in a meadow! My immediate answer was that in that case no uranium ore deposits could exist; they would have blown up long ago by the explosive multiplication of neutrons in them. However, I quickly saw that my argument was too naive; ores contained lots of other elements which might swallow up the neutrons; and the seams were perhaps thin, and then most of the neutrons would escape. So from Møller's remark the exciting vision arose that by assembling enough pure uranium (with appropriate care!) one might start a controlled chain reaction and liberate nuclear energy on a scale that really mattered. Many others had the same thought, as I soon found out. Of course the specter of a bomb—an uncontrolled chain reaction—was there as well; however, for awhile anyhow, it looked as though it need not frighten us. That complacency was based on an argument of Bohr, which was subtle but appeared quite sound."[2]

The February 15, 1939 issue of the Physical Review contained a two page article by Bohr that changed everything.[3] It had the unremarkable title "Resonance in uranium and thorium disintegrations and the phenomenon of nuclear fission." The essential point came in the penultimate paragraph and might easily have been overlooked. Bohr noted that what counts in the fission process is the formation of a compound nucleus after the incident neutron has been absorbed. For ^{238}U, the common isotope, it is ^{239}U, while for ^{235}U, the rare isotope, it is ^{236}U. The latter is an even-even nucleus, while the former is an even-odd nucleus and hence more loosely bound. This difference in binding energies results in a difference in the mass defect between the initial state of the neutron and one of the isotopes of uranium and the compound nucleus. This difference for the uranium isotopes is about 1.7 Mev. The extra energy due to this mass defect goes into the excitation energy of the compound nucleus and is what is responsible for its fission. To make ^{238}U fission we must supply an energy of at least 1 MeV from the incident neutron while for ^{235}U this energy is supplied by the mass defect and hence neutrons of any energy can cause fission. This energy threshold or lack of same is the difference between a "fissionable" and a "fissile" nucleus.

Frisch's complacency and Bohr's as well had to do with the realization that the dominant isotope could not make a self-sustaining chain reaction. Much of the spectrum of the emitted neutrons would be below the threshold energy for fission. Thus, to make such a chain reaction would require the separation of isotopes on an industrial scale. Bohr ruled this separation out because he said it would take the resources of an entire country. Actually, it took the resources of three: Great Britain, the United States, and Canada. However, up to this point no one had actually determined how much ^{235}U was needed to make a "critical mass"—a mass above which the chain reaction would be self-sustaining. Enter Rudolf Peierls.

Peierls was born in Berlin in 1907 which made him three years younger than Frisch who was born in Vienna. Both men were of Jewish ancestry. Peierls, who was a theorist, took his degree in Munich from Arnold Sommerfeld. Sommerfeld was one of the great teachers of physics with such star pupils as Heisenberg, Pauli, and Bethe. As Peierls moved up the academic ladder, he too set up schools of theoretical physics, first at Manchester, then Birmingham, and finally in Oxford. For a while he was an assistant to Pauli who complained that Peierls was so fast that after telling you about an idea he would tell what was wrong with it before you had a chance to grasp the original idea. He made significant contributions in every branch of theoretical physics. When Hitler came to power, Peierls was in Cambridge on a Rockefeller Scholarship. He stayed in Britain in different positions until he was named a professor of physics in Birmingham in 1937.

When fission was discovered, it was natural that Peierls would take an interest. The first question he addressed was how to make a chain reaction. In 1939 he published a paper in the Proceedings of the Cambridge Philosophical Society[4] entitled "Critical conditions in neutron multiplication." The first paragraphs of this paper read:

"It is well known that a single neutron may cause a nuclear reaction chain of considerable magnitude, if it moves in a medium in which the number of secondary neutrons which are produced by neutron impact is, on the average, greater than the number of absorbed neutrons. From recent experiments it would appear as if this condition might be satisfied in the case of uranium.

Such multiplication of neutrons can only take place if the path traveled by each neutron in the body is long enough to give it a sufficiently high chance of making a collision. It seems of some interest to discuss the dependence of the phenomenon on the size of the body."[5]

Let me restate these ideas in somewhat different language. Suppose a solid sphere of uranium has been assembled. In his paper, Peierls does not specify the isotope. In the interior of the sphere neutrons are being produced in the fission products. Within the sphere the neutrons can collide elastically and inelastically, they can be absorbed, or they can produce more fission products. However, the neutrons can also escape through the surface of the sphere. What we want to know is the critical radius of the sphere—the size at which the number of neutrons that escape just balances the number of neutrons that are created. If we know this critical radius, we know the volume of the sphere and from the mass density we then know the critical mass. At just this mass there is no self-sustaining chain reaction produced. We need a "supercritical" mass. This idea was tested and confirmed in the Godiva experiments at Los Alamos.[6] Frisch participated and gave its name because bare masses were being used. In an actual bomb the fissile sphere is surrounded by a heavy metal casing that reflects neutrons and thus enhances the fission reactions.

The fission mean free path for the neutrons, the average distance between fissions, is roughly the order of magnitude of the critical radius. The Peierls theory refines this estimate. The mean free path for fission is by definition $r_f = 1/n\sigma_f$. Here, n is the number density of the uranium nuclei in the sphere and σ_f is the fission cross section. Curiously, Peierls did not put in any numbers to estimate this mass. This estimation was left to Frisch. Frisch had a good idea on the order of magnitude of n, but not much of an idea about σ_f. In his paper, Bohr wrote that this cross section for fission can never "exceed nuclear dimensions."[7] If we apply this statement literally and take the radius of a uranium nucleus to be about 7 F (10^{-15} m), equal to about 7×10^{-13} cm, then the area is about 1.5×10^{-24} cm^2 $= 1.5$ b.

What Frisch and Peierls did not know was that this cross section was being measured for slow neutrons on trace amounts of ^{235}U that had been electromagnetically separated in a collaboration between Alfred O. Nier of the University of Minnesota and E. T. Booth, J. R. Dunning, and A. V. Grosse of Columbia University. In March of 1940 they announced results of somewhere between 400 and 500 b.[8] The huge discrepancy between this result and Bohr's estimate has to do with quantum mechanics. Once the neutron is slowed down to where its de Broglie wavelength is about the size of the target—the uranium atom—the classical geometric picture no longer applies. (A thermal neutron which has an energy of about 0.025 eV has a de Broglie wavelength of about 1.8 Å.) All Frisch could do was to make a guess at the fission cross section, and he took it to be about 10 b or 10^{-23} cm^2, which for the energy region that is relevant—say 2 MeV—is one order of magnitude too large. This overestimate reflects itself in the critical mass which goes as the cube of the radius and hence of the inverse cross section. Frisch found a critical mass that was the order of a pound or so—much too small. The actual critical mass of ^{235}U is about 115 lbs.

Having found this small critical mass Frisch alerted Peierls and began thinking of ways in which he could actually separate the uranium isotopes. First the latter.

Frisch was familiar with a method that had been invented in 1938 in Germany by the German physical chemist Klaus Clusius and his younger colleague Gerhard Dickel.[9] In essence the separation apparatus consists of a vertical tube with a wire down the middle that can be heated. If a gas with different isotopes is introduced, the lighter isotope concentrates at the heated element and accumulates at the top, while the heavy element, as a kind of countercurrent, accumulates at the bottom. In 1939 Clusius announced the separation of chlorine isotopes using his method and he began collaboration with Paul Harteck and others to begin trying to separate uranium isotopes in a uranium hexafluoride gas. Frisch had no way of knowing that this method was unsuccessful. Apart from the corrosive effects of this gas, the high temperatures involved created instability in the uranium hexaflouride molecules, and the Germans switched their attention to using centrifuges. However, Frisch mastered enough of the difficult theory to realize that the efficiency of the process could be improved if a bigger tube rather a thin wire was used. He needed a glass blower to make the tube and these people had radar as a priority. While he was waiting for the equipment, he received an invitation to write a report for the British Chemical Society on advances in nuclear physics, and he included a section on fission and its prospects.

Neither Frisch nor Peierls was British citizen. In fact, they were classified as enemy aliens, which meant that they could not work on any secret military program including radar. However, Oliphant, Peierls' colleague at Birmingham, got around this problem by posing questions to Peierls that were in the guise of abstract problems in electromagnetism. Peierls knew they were connected to radar and Oliphant knew that he knew, but the security fiction was preserved.

Peierls now took the prospect of nuclear weapons very seriously, which led to two memoranda, one of which I am going to deconstruct. After I finish this exercise I will discuss what happened to these memoranda. I will present the memorandum line by line and add my comment (comments in square brackets).

The memorandum was titled "On the construction of a 'superbomb' based on a nuclear chain reaction in uranium" (March 1940).[10] The date is significant because it sets limits of what Frisch and Peierls knew. For example, the paper by Nier *et al.*[8] was published after this date. In the following all quotations are from the memorandum, and my comments are contained within brackets.

"The possible construction of superbombs based on a nuclear chain reaction has been discussed a great deal and experiments have been brought forward which seemed to exclude this possibility. We wish here to point out and discuss a possibility that seems to have been overlooked in these earlier discussions." [I wonder what discussions are being referred to. The new possibility is the role of ^{235}U.]

"Uranium consists essentially of two isotopes, ^{238}U (99.3%) and ^{235}U (0.7%). If a uranium nucleus is hit by a neutron, three processes are possible: (1) scattering, whereby the neutron changes directions and if its energy is above 0.1 MeV, loses energy; (2) capture, when the neutron is taken up by the nucleus; and (3) fission, i.e., the nucleus breaks up into two nuclei of comparable size, with the liberation of an energy of about 200 MeV." [I confess that when I first read the memorandum, I found the first of the three possibilities incomprehensible as discussed by these authors, but I have been able to deconstruct what they meant.[11] For elastic scattering the incident neutron can lose energy. If we average over all angles and call the average final energy $E_{\mathrm{f,av}}$ and the initial energy E, then $E_{\mathrm{f,av}}/E=(1+(A-1)^2/(A+1)^2)/2$. Here, A is the mass number. This expression tells us why heavy elements such as uranium are poor moderators. If we substitute $A=235$ in this expression, we find $E_{\mathrm{f,av}}/E \approx 0.99$, which means that it takes a couple of thousand elastic collisions to thermalize neutrons with a uranium moderator. The separation of the energy levels in these heavy elements near the ground state is about 0.1 MeV. This energy is the threshold for inelastic scattering and is a measure of the energy loss in such an event.]

"The possibility of a chain reaction is given by the fact that neutrons are emitted in the fission and that the number of these neutrons per fission is greater than 1. The most probable value for this figure seems to be 2.3, from two independent determinations.

"However it has been shown that even in a large block of ordinary uranium no chain reaction would take place since too many neutrons would be slowed down by inelastic scattering into the energy region where they are strongly absorbed by ^{238}U.

"Several people have tried to make chain reaction possible by mixing uranium with water, which reduces the energy of the neutrons still further and thereby increases their efficiency again. It seems fairly certain, however, that even then it is impossible to sustain a chain reaction." [I wonder what people. If a heavy water moderator is used, then chain reactions can be sustained with natural uranium, which is what the Germans tried to do in their reactor program.]

"In any case, no arrangement containing hydrogen and based on the notion of slow neutrons could act as an effective superbomb because the reactions would be too slow. The time required to slow down a neutron is about 10^{-5} s, and the average time lost before a neutron hits a uranium nucleus is even 10^{-4} s." [Unfortunately Frisch and Peierls do not give us any information on how they arrived at these numbers. I will try to make their argument and use the data that is now available. The idea of using an arrangement using hydrogen was also later considered at Los Alamos. The motivation was to take advantage of the $1/v$ law for fission cross sections. We have seen that Nier *et al.*[8] measured these cross sections for slow neutrons to be several hundred barns. This method was also abandoned at Los Alamos because it was too slow. Let us try to understand the 10^{-5} s time required for the thermalization of the neutrons; that is, the reduction of the average neutron energy from about 2 MeV to the thermal energy of 0.025 eV by elastic collisions of neutrons with hydrogen. For the sake of argument I will take the elastic cross section to be 20 $\mathrm{b}=2\times 10^{-23}$ cm^2. We will use this number to estimate the mean free path for elastic scattering. I will take the number density of water to be $\approx 3.3\times 10^{22}/\mathrm{cm}^3$. Therefore, the mean free path for elastic scattering is about 1.5 cm. It takes about 18 elastic collisions of neutrons with water molecules to thermalize the neutron. During this time it travels about 27 cm, which means that to have a thermalization time of 10^{-5} s, the speed of the neutrons would have to be about 3×10^6 cm/s, which is somewhat faster than the thermal speed of 2.2×10^5 cm/s but considerably slower than the fission neutrons which move at a speed of about a tenth that of light. I have no way of knowing if this reasoning is what Frisch and Peierls did but their answer seems reasonable. I will not derive the mean free path for fission here but leave it to later. With their choice of parameters Frisch and Peierls claim that the mean free path is 2.6 cm. If we divide this value by the thermal speed, we obtain like 10^{-4} s noted previously. Later I will explain why this time is much too short for the slow neutrons to play a role in the explosive chain reaction.]

"In the reaction, the number of neutrons should increase exponentially, like $e^{t/\tau}$ where τ would be at least 10^{-4} s." [Later I am going to use this exponential to determine the time it takes to fission a kilogram of ^{235}U using the value of τ for fast neutrons. Often in this discussion, assuming that two neutrons are created per fission, this exponential is replaced by 2^x where x is the number of generations. This doubling is really not correct and should be replaced by an exponential tail. I also emphasize that most of the neutrons are created in the last couple of iterations.] "When the temperature reaches several thousand degrees the container of the bomb will break and within 10^{-4} s the uranium would have expanded sufficiently to let neutrons escape so to stop the reaction. The energy liberated would, therefore, be only a few times the energy required to break the container, i.e., of the same order of magnitude as with ordinary high explosives." [What is being said here is that with an exponential folding time of 10^{-4} s for the creation of neutrons, the uranium will have expanded enough so that the density is once again below critical and the bomb shuts off before producing a substantial amount of energy.]

"Bohr has put forward strong arguments for the suggestion that the fission observed with slow neutrons is to be ascribed to the rare isotope ^{235}U and that this isotope has on the whole, a much greater fission probability than the common isotope ^{238}U. Effective methods for the separation of isotopes have been developed recently, of which the method of thermal diffusion is simple enough to permit separation of a fairly large scale." [They are still optimistic about the Clusius-Dickel method which did not work out.] "This permits, in principle, the use of nearly pure ^{235}U in such a bomb, a possibility which apparently has not so far been seriously considered. We have discussed this possibility and have come to the conclusion that a moderate amount of ^{235}U would indeed constitute an extremely efficient explosive.

"The behavior of ^{235}U under bombardment with fast neutrons is not known experimentally, but from rather simple theoretical arguments it can be concluded that almost every collision produces fission and that neutrons of any energy are effective." [I am a little puzzled by the statement that almost every collision produces fission. The cross section for inelastic scattering, for example, is comparable to that of fission. Frisch and Peierls overestimated the size of the fission cross section. There are about five elastic collisions between fissions.] "Therefore it is not necessary to add hydrogen, and the reaction, depending on the action of fast neutrons, develops with great rapidity so that a considerable part of the total energy is liberated before the reaction gets stopped on account of the expansion of the material.

"The critical radius r_0, i.e., the radius of a sphere in which the surplus of neutrons created by the fission is just equal to the loss of neutrons by escape through the surface, is for a material with a given composition in a fixed ratio to the mean free path of the neutrons and this in turn is inversely proportional to the density. It therefore pays to bring the material to the densest possible form, i.e., the metallic state probably sintered or hammered." [The mass goes as ρ times the volume of the sphere, that is, $\sim r^3\rho$. Because the mean free path goes as $1/\rho$, the critical mass goes as $1/\rho^2$. This quadratic dependence has a very important application in implosion weapons. Before the sphere is imploded the mass is subcritical at normal densities. However, when the sphere is shrunk the density increases and the same mass becomes supercritical.] "If we assume for ^{235}U, no appreciable scattering, and 2.3 neutrons emitted per fission, then the critical radius is found to be 0.8 times the mean free path. In the metallic state (density 15) and assuming a fission cross section of 10^{-23} cm^2, the mean free path would be 2.6 cm and r_0 would be 2.1 cm corresponding to a mass of 600 g. A sphere of metallic ^{235}U of a radius greater than r_0 would be explosive and one might think about 1 kg as a suitable size for a bomb."

[This paragraph is arguably the most significant passage in the memorandum and it is substantially wrong. The Hiroshima bomb required 64 kg of uranium, 50 kg of which were 89% enriched and the remaining 14 kg were 50% enriched, leading to a total of about 52 kg of ^{235}U. As I have mentioned, we can only wonder if at this time the British would have pursued their program with the same intensity if the real figures had been known. Now to the production of these figures.

I will begin by deriving the correct mean free path for fission by fast neutrons of ^{235}U. First we need the cross section. Then I will discuss the sort of numbers that were available to Frisch and Peierls at the time they wrote their memorandum. A modern value is $\sigma_f = 1.24$ b with a small error. We next need the number of ^{235}U nuclei per cubic centimeter for metallic uranium. The density of metallic ^{235}U is about 19 g/cm^3. Frisch and Peierls used 15 g/cm^3. Each ^{235}U nucleus has a mass of about 3.9×10^{-22} g. Hence, the number per cubic centimeter is about 4.9×10^{22}. Thus, the mean free path is about 16.5 cm. With their various assumptions Frisch and Peierls found 2.6 cm.

They claim that the critical radius is 0.8 times the mean free path. Using their various numbers we have, by multiplying the volume V times the density, $M_c = 4/3\pi(0.8 \times 2.6)^3\ \text{cm}^3 \times 15\ \text{g/cm}^3 = 565$ g. The volume turns out to be 38 cm^3. For comparison the volume of a tennis ball is about 137 cm^3. It is little wonder that Peierls and Frisch were alarmed.

Let me redo the numbers using an expression for the critical mass that can be derived reasonably straightforwardly.[12] This methodology is less sophisticated than the 1939 paper of Peierls.[4] Hence, we do not expect it to yield a precise answer. The expression for the critical radius in terms of the mean free path is $r_c = (\pi/\sqrt{3})(r_f/\sqrt{\nu - 1})$, where ν is the average number of neutrons produced per fission, which I will take as 2.5. Here r_f is the fission mean free path which is about 16.5 cm. This expression gives a critical radius of 24.4

cm, and with the correct density we obtain a critical mass of about a metric ton. This value is much too big and shows that this calculation must be done with care. Indeed this expression is only applicable in the approximation used by Frisch and Peierls that there is no elastic scattering. Otherwise, we have to replace r_f by $\sqrt{r_f r_{total}}$, where r_{total} is the total mean free path including elastic scattering. Because $\sqrt{r_f r_{total}}$ is smaller than the fission mean free path, the critical mass is less.

Now I turn to the numbers used by Frisch and Peierls. This consideration is conjectural because there are no references or acknowledgments in their memorandum. The date of their memorandum is March 1940, which presumably means that anything published after that date would be inaccessible to them unless it had been communicated by preprint or private communication. They did know of Bohr's February publication of the role of ^{235}U.[3] However, we can look for clues in the papers that they had published prior to the memorandum, starting with the 1939 paper by Peierls.[4] There is only one relevant reference in this paper, and it is by Perrin.[13] Perrin apparently had not heard of Bohr's work so he seems to have tried to make a chain reaction using natural uranium. He somehow arrived at a critical radius of 130 cm and a critical mass of 40 metric tons. He concluded that it is impossible to make a chain reaction using fast neutrons and natural uranium and suggests slowing them with hydrogen. The only relevant subject in Perrin's paper is the idea of a critical mass.

A paper that Frisch and Peierls must have seen is entitled "The scattering by uranium nuclei of fast neutrons and possible neutron emission resulting from fission" by Goldstein *et al.*, published on July 29, 1939.[14] This paper presents a measurement of the fission cross section of fast neutrons incident on uranium. There are four problems with this measurement: the uranium is not separated, the uranium is in the form of uranium oxide, the neutron energy spectrum is not precisely known, and most importantly, the measurement measures the total cross section, which includes elastic and inelastic scatterings as well as fission. Nonetheless, the authors conclude that the fission cross section is about 10 b. They note the agreement of this number with an earlier measurement done at Columbia University by a group that included Fermi. It is therefore not surprising that Frisch and Peierls took 10 b as the fission cross section when they estimated the critical mass.]

"The speed of the reaction is easy to estimate. The neutrons emitted in the fission have velocities of about 10^9 cm/s and they have to travel 2.6 cm before hitting a uranium nucleus. For a sphere well above the critical size the loss through neutron escape would be small, so we may assume that each neutron, after a life of 2.6×10^{-9} s, produces fission, giving birth to two neutrons. In the expression $e^{t/\tau}$ for the increase of neutron density with time, τ would be about 4×10^{-9} s, very much shorter than in the case of a chain reaction depending on slow neutrons." [Let me make the same point by asking a somewhat different question but using the correct numbers. How much time does it take to fission a kilogram of ^{235}U using fast neutrons? First, the time given by Frisch and Peierls should be replaced by $\tau = 16.5\ \text{cm}/10^9\ \text{cm/s} = 1.65\times10^{-8}$ s. The number of ^{235}U nuclei in a kilogram is about 2.6×10^{24}. Thus, we must solve the equation $2.6\times10^{24} = \exp(t/1.65\times10^{-8})$ for t, which gives t equal to about a microsecond, which makes the point about the rapidity of fission with fact neutrons.] "If the reaction proceeds until most of the uranium is used up, temperatures on the order of 10^9 K and pressures of about 10^{13} atm are produced. It is difficult to predict accurately the behavior of matter under these extreme circumstances, and the mathematical difficulties of the problem are considerable. By a rough calculation we get the following expression for the energy liberated before the mass expands so much that the reaction is interrupted:

$$E = 0.2M(r^2/\tau^2)\sqrt{(r/r_0 - 1)}, \tag{1}$$

where M is the total mass of uranium, r is the radius of the sphere, r_0 is the critical radius, and τ is the time required for the neutron density to multiply by a factor e. For a sphere of diameter of 4.2 cm (r_0=2.1 cm, M=4700 g, and τ=4 $\times10^{-9}$ s), we find $E=4\times10^{22}$ erg."

[This paragraph must be deconstructed. First, Eq. (1), which is given in Serber,[10] is wrong. The correct formula, which is found in the original paper at the Bodelian Library at Oxford, is[15]

$$E = 0.2M(r^2/\tau^2)(\sqrt{r/r_0} - 1). \tag{2}$$

Equally wrong is the statement of Serber that the sphere has a diameter of 4.2 cm. This value would mean that the sphere has the critical radius and Eq. (1) would give zero. The original paper states that the sphere has a radius of 4.2 cm. If I substitute in the correct numbers into Eq. (2), I find a release of 4×10^{20} erg or 4×10^{13} J, which is in agreement with the Frisch and Peierls number. A kiloton of TNT produces 4.18 $\times10^{12}$ J. Choice of 4700 g of ^{235}U of Frisch and Peierls seems inexplicable.] "For a radius of about 8 cm (M =32 kg), the whole fission energy is liberated according to Eq. (1). For small radii the efficiency falls off even faster than indicated by this equation because τ increases as r approaches r_0. The energy liberated by a 5 kg bomb would be equivalent to that of several thousand tons of dynamite and that of a 1 kg bomb, though 500 times less, would still be formidable. [I leave it as an exercise for the reader to verify these numbers. I do not understand the remark about τ because this time seems to be fixed by the mean free path. The efficiency of the Hiroshima bomb was 1.5%, which means that of the 52 kg of ^{235}U, only about a kilogram was fissioned. The rest floated off into thin air.]

"It is necessary that such a sphere should be made in two (or more) parts, which are brought together when the explosion is wanted. Once assembled, the bomb would explode within a second or less since one neutron is sufficient to start the reaction and there are several neutrons passing through the bomb in every second from the cosmic radiation. (Neutrons originating from the action of uranium alpha rays on light element impurities would be negligible provided the uranium is reasonably pure.) A sphere with a radius of less than 3 cm could be made up in two hemispheres, which are pulled together by springs and kept separated by a suitable structure which is removed at the desired moment. A larger sphere would have to be composed of more than two parts, if the parts, taken separately, are to be stable.

"It is important that the assembling of the parts should be done as rapidly as possible in order to minimize the chance of a reaction getting started at a moment when the critical conditions have only just been reached. If this happened, the reaction rate would be much slower and the energy liberation would be considerably reduced; it would, however, always be sufficient to destroy the bomb.

"It may be well to emphasize that a sphere only slightly below the critical size is entirely safe and harmless. By experimenting with spheres of gradually increasing size and measuring the number of neutrons emerging from them under a known neutron bombardment, one could accurately determine the critical size, without any danger of a premature explosion." [Considering the technological tidal wave that this paper was about to unleash, these remarks seem rather naive. In an actual nuclear device it is not cosmic ray neutrons that start the chain reaction but rather an "initiator"—a device that produces neutrons when the shock waves from the forced assembly of the subcritical parts strike it. These neutrons are produced when the assembly becomes supercritical. There is also something charming about the notion of this assembly being produced by the actions of "springs." The kinds of experiments needed to determine the critical mass were carried out at Los Alamos, some of which by Frisch. Feynman referred to them as "tickling the tail of the sleeping dragon."]

"For the separation of ^{235}U, the method of thermal diffusion, developed by Clusius and others, seems the only one which can cope with the large amounts required. The gaseous uranium compound, for example, uranium hexafluoride, is placed between two vertical surfaces which are kept at a different temperature. The light isotope tends to get more concentrated near the hot surface, where it is carried upwards by the convection current. Exchange with the current moving downwards along the cold surface produces a fractionating effect, and after some time a state of equilibrium is reached when the gas near the upper end contains markedly more of the light isotope than near the lower end.

"For example, a system of two concentric tubes of 2 mm separation and 3 cm diameter, 150 cm long, would produce a difference of about 40% in the concentration of the rare isotope between its ends, and about a gram a day could be drawn from the upper end without unduly upsetting the equilibrium.

"In order to produce large amounts of highly concentrated ^{235}U, a great number of these separating units will have to be used, being arranged in parallel as well as in series. For a daily production of 100 grams of ^{235}U of 90% purity, we estimate that about 100000 of these tubes would be required. This seems a large number, but it would undoubtedly be possible to design some kind of system which would have the same effective area in a more compact and less expensive form." [Once the real work began, the Clusius method was set aside. It is interesting that Frish and Peierls are already considering the design of "cascades" in which the parallel elements allow one at any stage to take on more material while the serial elements produce the separation.]

"In addition to the destructive effect of the explosion itself, the whole material of the bomb would be transformed into a highly radioactive state. The energy radiated by these active substances will amount to about 20% of the energy liberated in the explosion, and the radiations would be fatal to living beings even a long time after the explosion.

"The fission of uranium results in the formation of a great number of active bodies with periods between, roughly speaking, a second and a year. The resulting radiation is found to decay in such a way that the intensity is about inversely proportional to the time. Even 1 day after the explosion the radiation will correspond to a power expenditure on the order of 1000 kW or to the radiation of a hundred tons of radium.

"Any estimate of the effects of this radiation on human beings must be rather uncertain because it is difficult to tell what will happen to the radioactive material after the explosion. Most of it will probably be blown into the air and carried away by the wind. This cloud of radioactive material will kill everybody within a strip estimated to be several miles long. If it rained the danger would be even worse because active material would be carried down to the ground and stick to it, and persons entering the contaminated area would be subjected to dangerous radiations even after days. If 1% of the active material sticks to the debris in the vicinity of the explosion and if the debris is spread over an area of, say, a square mile, any person entering this area would be in serious danger, even several days after the explosion.

"In these estimates the lethal dose of penetrating radiation was assumed to be 1000 R; consultation of a medical specialist on x-ray treatment and perhaps further biological research may enable one to fix the danger limit more accurately. The main source of uncertainty is our lack of knowledge as to the behavior of materials in such a superexplosion, and an expert on high explosives may be able to clarify some of these problems.

"Effective protection is hardly possible. Houses would offer protection only at the margins of the danger zone. Deep cellars or tunnels may be comparatively safe from the effects of radiation, provided air can be supplied from an uncontaminated area (some of the active substances would be noble gases which are not stopped by ordinary filters).

"The irradiation is not felt until hours later when it may be too late. Therefore, it would be very important to have an organization which determines the exact extent of the danger area, by means of ionization measurements, so that people can be warned from entering it."

The subject of damage from nuclear weapons is immensely complex and Frisch and Peierls barely scratch the surface. The memorandum is signed O. R. Frisch and R. Peierls, The University, Birmingham.

Having written the report the question was what to do with it. They thought that it was so sensitive that Peierls typed it himself. They gave it to Oliphant who got it into the hands of Henry Tizard. Tizard was an Oxford chemist who was in charge of a committee that was studying scientific applications to wartime activities—at the time, mainly radar. They had a subcommittee that had looked into nuclear weapons, but they had decided that they were not feasible so the subcommittee was in the process of disbanding. They had considered only slow neutrons so that the Frisch-Peierls memorandum was a revelation.

Frisch and Peierls were informed that as "enemy aliens" they were to have nothing further to do with the matter. Peierls wrote a letter addressed to whoever was running whatever committee was doing this work that this position was absurd because he and Frisch knew more about this than anyone. It turned out that a new committee had been formed with the name MAUD. The reason for this name is one of the legends of the nuclear age.

Lise Meitner happened to be in Copenhagen when the Germans occupied the city in 1940. Bohr asked her to send a message to his British colleagues when she returned to Sweden. Apparently, she had no trouble getting back and wired to a friend in England: "Met Niels and Margrethe recently. Both well but unhappy about events. Inform Cockcroft and Maud Ray Kent."[16] John Cockcroft was a Cambridge physicist whom Bohr had gotten to know, but who was "Maud Ray Kent"? The recipients of the message were sure that this name was a code and that what was concealed had to do with nuclear energy. However, try as they did, they could not crack the "code." It was revealed a few years later that Maud Ray was a governess that had taken care of the Bohr children on one of their visits to England and that she lived in Kent.

In the fall of 1940 Tizard led a mission to the United States (Cockcroft and Oliphant came along) to present the results of Frisch and Peierls and the MAUD committee to various American scientists. No one was much interested. What interest there was in the use of nuclear energy for power generation and in radar, which was the central mission of the committee. However, Oliphant acted like a man possessed. He simply would not be contained when it came to discussing the prospects of a bomb. He button-holed everyone and is as responsible as anyone for getting the program revived here. There is some irony here because it was Oliphant who brought Frisch to England, which began the chain of events that finally lead to the memorandum we have been discussing.

The MAUD committee produced its final report in July of 1941.[17] It begins rather oddly. "We would like to emphasize at the beginning of this paper that we entered the project with more skepticism than belief, though we felt that it was a matter that had to be investigated. As we proceeded we became more and more convinced that release of atomic energy on a large scale is possible and that conditions can be chosen which would make it a very powerful weapon of war."[18] The body of the paper, in which Frisch and Peierls along with other prominent British scientists played a role, is one order of magnitude more sophisticated than the original Frisch-Peierls memorandum. Gone, for example, are the springs. They are replaced by high explosives—a "gun assembly"—a bomb like that of the Hiroshima weapon. Gone is the Clusius thermal diffusion method of isotope separation. It just did not work and is replaced by gas diffusion through a membrane pierced by tiny holes. Better values are available for the neutron cross sections and a modified critical mass of between 9 and 43 kg is presented. There are proposals to work with British industry. It is clearly a plan of action.

The MAUD committee was replaced by "tube alloys"—a code name for the British atomic bomb project. In November of 1941 Columbia University scientists Harold Urey and George Pegram attended the first meeting. They realized just how serious this nuclear weapon program was and spread the word when they got back to the United States. We can see the influence that the Frisch-Peierls memorandum had.

Both Frisch and Peierls went to Los Alamos as part of the British delegation. After the war they returned to England. In 1968 Peierls was knighted. Frisch also received several awards from his adopted country. He died in 1979 and Peierls in 1995.

ACKNOWLEDGMENTS

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[1] Otto Frisch, *What Little I Remember* (Cambridge U. P., New York, 1979).
[2] Reference 1, p. 118.
[3] N. Bohr, "Resonance in uranium and thorium disintegrations and the phenomenon of nuclear fission," Phys. Rev. **55**, 418–419 (1939).
[4] R. Peierls, "Critical conditions in neutron multiplication," Proc. Cambridge Philos. Soc. **35**, 610–615 (1939).
[5] Reference 4, p. 610.
[6] U.S. Department of Energy, "Criticality experiments facility," National Nuclear Security Administration Nevada Site Office, 2005-06-15 ⟩www.nv.doe.gov/library/factsheets/DOENV_1063.pdf.
[7] Reference 3, p. 419.
[8] A. O. Nier, E. T. Booth, J. R. Dunning, and A. V. Grosse, "Nuclear fission of separated uranium isotopes," Phys. Rev. **57** (6), 546 (1940).
[9] Klaus Clusius and Gerhard Dickel, "Zur trennung der chlorisotope," Naturwiss. **27**, 148–149 (1939).
[10] There are several places where this memorandum can be found. My choice is in an appendix of Robert Serber, *The Los Alamos Primer* (University of California Press, Berkeley, 1992). The advantage is that the reader can get a tutorial in bomb physics in the rest of the book. Also it is one of the more accessible choices. The reader should be warned that there are several significant mistakes in this version, which Cameron Reed has been able to compare to the original in the Bodleian Museum at Oxford. I will point out these mistakes as we go along.
[11] I am grateful to Carey Sublette for his help in sorting this out.
[12] See, for example, J. Bernstein, "Heisenberg and the critical mass," Am. J. Phys. **70** (9), 911–916 (2002).
[13] F. Perrin, "Calcul relative aux conditions éventuelles de transmission en chaine dl'uranium," C. R. Acad. Sci. URSS **208**, 1394–1396 (1939).
[14] L. A. Goldstein, A. Rogozinski, and R. J. Walen, "The scattering by uranium nuclei of fast neutrons and the possible neutron emission resulting from fission," Nature (London) **144**, 201–202 (1939).
[15] I thank Cameron Reed who has seen the manuscript for communications on this matter. I will not present a derivation because it would take us into too much technical detail.
[16] See, for example, Richard Rhodes, *The Making of the Atomic Bomb* (Simon and Schuster, New York, 1986), p. 340.
[17] To read the report, see Margaret Gowing, *Britain and Atomic Energy 1939–1945* (Macmillan, London, 1964). You will also find a version of the Frisch-Peierls memorandum which is less error prone than the Serber version.
[18] Reference 13, p. 594.