# Nuclear Demons, Nuclear Dreams

## Hans Bethe

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*The sun has been shining for billions of years, but it took a Hans Bethe (pronounced Bay-te) to figure out just how it works. His discovery, made in 1938, was the culmination of his work in the then-dawning field of nuclear physics. For nearly twenty years a number of very good physicists had been speculating on the kinds of nuclear reactions that might take place deep within the interior of the sun and other stars to provide the sunlight and starlight we receive. Bethe did more than speculate; he approached the problem systematically. Picking and choosing adroitly among the possibilities, he put together two sequences of nuclear reactions — the proton-proton cycle and the carbon cycle — then showed that, under conditions to be expected in the interior of the sun and other stars, these sequences would indeed produce energy at the observed rates. For this, he was awarded the Nobel Prize in physics in 1967.*

*Born in 1906, in Alsace-Lorraine, then part of Wilhelminian Germany, Bethe was one of the generation of brilliant physicists who flourished in Europe during the 1920s and early 1930s, when modern atomic theory was being born. Adolf Hitler's rise to power, in the early 1930s, presaged the end of that scientific renaissance, and in 1935 Bethe immigrated to the United States, where Cornell University has been his home base ever since.*

*Like most of his colleagues, Bethe was taken aback by the discovery,*

*Photograph: David M. Kennedy*

*in 1939, of a new kind of nuclear reaction — the splitting of uranium. He knew from the outset that, with war looming, this discovery of fission could lead to the development of an atom bomb. By 1942, he was convinced that the bomb could be ready in time to be used during the war. He then joined the Manhattan Project and soon rose to direct the Division of Theoretical Physics at Los Alamos, New Mexico. For his work on the project he received the Presidential Medal of Merit from Harry S. Truman in 1946.*

*Bethe's exceptional understanding of physics, his background in government service, and his ability to address a broad range of scientific problems made him a natural leader in the world of postwar physics. He was one of the founders of the Big Bang theory of the origin of the universe. He also contributed to some of the earliest studies on power-producing nuclear reactors and, in 1949, wrote the first paper on the safety of fast-breeder reactors. Along with many of the other senior leaders of the Manhattan Project, he was disturbed by the implications of his work. This concern led him into the world of public policy. During the 1950s Bethe served as a member of the President's Science Advisory Committee, which dealt with nuclear safety issues at the highest government levels.*

*In recent years, Bethe has not hesitated to plunge full tilt into debates over nuclear power. In a controversial article published in* Scientific American *in 1976, Bethe asserted that during the next quarter-century nuclear energy will be the only alternative to fossil fuels. "The general public is not well enough informed about science and technology and our role in our society," he wrote. "This allows any number of nuts to dispense misinformation couched in noble rhetoric." Taking his lead from antinuclear activists, he went on to marshal dozens of his fellow scientists as signers of a pronuclear petition arguing that objections to nuclear power should be outweighed by the benefits it would provide.*

*Today Bethe continues to be a vigorous nuclear advocate who looks ahead to the presumed success of fusion power — the earliest studies of which drew directly from his encyclopedic writings on nuclear reactions. At the same time, he is fiercely opposed to nuclear weapons, speaking out for disarmament every chance he gets.*

*What does Bethe see as the future of the world's energy supplies, of nuclear power, of fusion, and of physics? To find out, T. A. Heppenheimer, author of* The Man-Made Sun, *a study of fusion, interviewed*

*Bethe in 1982 at the California Institute of Technology, in Pasadena, where he was a visiting professor. In 1983, I met with Bethe in his large, utilitarian office at Cornell, where we discussed the early days of physics and nuclear arms. A synthesis of the two talks follows.*

OMNI: Dr. Bethe, you were born in Germany, and it was in Germany during the twenties and thirties that you became a physicist. You must have seen German science change drastically under the Nazis. Can you describe some of that?

BETHE: The Nazis were antiscientific. Everything was done by feeling rather than by reason. In addition, many of the leading scientists were Jews, or half-Jews subject to anti-Semitic laws. So Germany lost maybe half of the good young scientists because of that, and then made sure the others were stifled, held down. The best German theoretical physicist, Werner Heisenberg, was held in disgrace for a long time; he wasn't considered enough of a Nazi, and he was severely attacked. Young German students were told that the great thing was fighting for the fatherland, not studying science. Consequently, Germany is missing a generation of scientists. In the postwar era, it took quite a long time for German science to recover. And it has not yet reached its previous eminence, except in one respect. They have a fabulous high-energy laboratory in Hamburg, which is simply excellent. The scientists working there come from all over Europe, from the United States, and Germany too.

OMNI: How was it that you came to leave Germany?

BETHE: Well, I'm half-Jewish, which meant that by early in April of 1933 I could no longer hold any position at any German university. I could have worked in an industrial laboratory, but I wanted to do pure science. So the decision was clear: I left. And I am very happy that I left as early as I did.

OMNI: You were involved with nuclear fission literally from the beginning. You were at Cornell in 1939 when Niels Bohr arrived on the S.S. *Drottningholm* with the news that Otto Hahn and Fritz Strassmann of Germany had discovered how to split (or fission) a heavy atom into two lighter ones, releasing energy in the process. How did you hear the news?

BETHE: I learned about it, I think, from people around me who were talking about it. I had one physicist colleague at Cornell, Georg Placzek, who was terribly interested and began working on this immediately. Then I learned more about it at a little meeting of some theoretical physicists in Washington. This was in March of 1939, and the whole subject of the fission of uranium was discussed there. Generally, our sessions were open to the press, but in this case we closed the meeting.

[Enrico] Fermi and [Leo] Szilard both outlined the possibilities of a nuclear weapon based on the creation of a nuclear chain reaction. [In a nuclear chain reaction, a heavy atom like uranium splits into two lighter atoms and one or more neutrons, subatomic particles with zero charge. Each neutron is capable of splitting another uranium atom, which then releases neutrons of its own. When enough uranium is present, the reaction becomes self-sustaining, going faster and faster, until an explosion occurs.] It was not at all clear that all this could be done. But these people at least saw the possibility.

OMNI: When you first heard these presentations, how did you respond?

BETHE: I thought it was largely speculation, that it would take lots of experimentation before it would become a real possibility. I was interested in this, at the time, because of the impending war. But I thought it was unlikely that nuclear fission would lead to a weapon that could be useful in the war, and therefore I didn't want anything to do with it. Instead, I concerned myself with such matters as projectiles penetrating armor plate and with underwater pressure waves from explosions. Most important was radar. That was what I worked on in the early years of the war.

OMNI: Then you did not associate yourself with the group that included Fermi, Szilard, and Einstein?

BETHE: Not Einstein.

OMNI: Well, Einstein signed the letter to President Roosevelt in August 1939, warning the president that the Germans might be working on an atomic bomb.

BETHE: Definitely. He signed the letter, but he never, never worked on the bomb or on the Manhattan Project.

OMNI: So you were not associated with the early group of physicists who, in 1939, sought to bring the potentials of nuclear weaponry to the attention of the highest levels of the United States government.

BETHE: That's correct. Nor was I associated with the group that tried to find out whether it was a real possibility.

OMNI: And yet shortly afterward, beginning in 1943, you headed the theoretical physics group at Los Alamos . . .

BETHE: That I did, yes. I joined the project in the summer of 1942, when it was shown to me, in a secret briefing, that Fermi's chain reaction, which he'd set up under the stands in a squash court in Chicago, was almost certain to operate. I'd doubted we could get enough material to make a bomb, because neutrons generally cannot fission [or split] ordinary uranium, but only uranium-235, a lighter and very rare form of the element. But Fermi was able to slow the neutrons down by embedding the uranium in a pile of graphite. Once they are slowed, more of them get caught in uranium-235 than in the much more abundant uranium-238. I saw that the project had developed quite well and that there was a good chance we could probably have the material for an atomic bomb during the war. And I did want to influence the outcome of the war — I was afraid, like most other people, that the Germans would build the bomb first.

OMNI: How did you get into that position in Los Alamos?

BETHE: I was a well-known nuclear theorist. Apart from Robert Oppenheimer, who was the leader of the project, and Eugene Wigner, who was busy at Chicago, I was probably the most knowledgeable person in nuclear physics.

OMNI: Have you seen the TV series "Oppenheimer"? How do you feel about its portrayal of your colleagues and of yourself?

BETHE: I watched it regularly. On the whole it reflected the spirit of Los Alamos very well and presented very good characterizations of my colleagues. As for Oppenheimer himself, it was very good, except that I don't believe — in the second episode — Oppenheimer tried quite so hard to persuade General Leslie Groves to make him director of the project. And I never lost my temper in Oppie's office while complaining about Edward Teller. And there are other mistakes. Some things are more dramatized than others; for instance, in episode five, the incident of Groves and Oppenheimer taking George Kistiakowsky to task [over a failed simulation of the bomb detonation]. That wasn't correct. But these are not really major criticisms.

OMNI: Once ensconced in your position at Los Alamos, what were some of the major technical problems you faced in developing the bomb, and how did you solve them?

BETHE: Well, the problem at Los Alamos was to get the bomb assembled. One problem was that, when we started, there was no appreciable amount of material available on which to do experiments. So, much of our time was spent trying to calculate, theoretically, how such a weapon would work, beginning with the amount and density of material [the critical mass] we'd need to start an explosion. That would tell us how much fissionable material the large facilities, such as those at Oak Ridge and Hanford, would have to produce. Second, we wanted to figure out how much energy could come out from such a device and what it would do in less than one-millionth of a second.

OMNI: Solving these problems would have required a great deal of computation. There were no electronic computers in those days. What did you do?

BETHE: To begin with, we had adding machines that you turned with a crank — we had cranking machines by the dozens, and a number of people who operated these hand calculators. But we also had electromechanical computers — the old IBM machines. They combined electric sensing — reading data off punch cards — with mechanical computation. They were quite good. They could add, subtract, multiply, and divide at fairly good speed. A major multiplication might take them a second. And there were very high-class physicists and mathematicians engaged in writing the programs. One of them was Richard Feynman, at Cal Tech. There were three very knowledgeable people helping him, as well as others less trained. They kept the machines in running order. One of my friends said at a later time, "These are my card-carrying Ph.D.s."

OMNI: Despite all the expertise, you had a major upset midway through the project. Can you talk about it?

BETHE: In addition to a uranium bomb, we were also building a plutonium bomb. It turned out that plutonium gave off neutrons spontaneously, threatening to predetonate the bomb slowly, creating a fizzle rather than a bang. That was quite a surprise: it showed that we could not assemble a plutonium weapon by the so-called gun method, in which the explosion occurred when two halves of a spherical bomb were shot together. We had to find a faster way to detonate the bomb, and we finally did. We took a quantity of plutonium, somewhat below critical mass, and surrounded it with powerful explosives. When we detonated the explosives, they compressed the plutonium, greatly increasing its density until it reached critical mass.

OMNI: The first test bomb was exploded at the Alamogordo, New Mexico, test site on July 16, 1945. Did you have any moral question about your work at that point?

BETHE: Not at that point. The real moral dilemma came not after the successful test, but after the bomb [a uranium bomb] was dropped on Hiroshima and we got the first photographs of the destruction. We had tried to calculate the damage, but the actual devastation was a lot worse, and seeing it in pictures means a lot more than just having the figures before you. Many of us at Los Alamos soon came to believe that we had to prevent nuclear weapons from ever being used again.

OMNI: What did you do toward that end?

BETHE: I gave a lot of talks around the country, and I collaborated with Fred Seitz on an article in a book called *One World or None.* Our article said that a determined country could surely repeat our performance and build an atom bomb within five years, but we were wrong by one year. It took the Russians four years. In fact, one of my friends recently talked to a Russian who said that Stalin ordered physicists to build the bomb in 1943, in the middle of very serious fighting. This, of course, we were not aware of in 1945, but it gave them a two-year start beyond what we knew. And the Russians wanted to have their own weapon.

We did not name the Russians in our article — that would not have been proper to do at that time. But we certainly had the Russians in mind, and our article was in complete contrast to the statements of the higher-ups, who told Congress it would take the Russians twenty years to build the bomb. Our contention was simply that the secret could not be kept. We were suggesting that it would do the United States no harm to join an international agency dedicated to arms control.

OMNI: Despite your efforts, nuclear weapons have proliferated to nightmarish proportions. Those in today's nuclear freeze movement even suggest we're in imminent danger of blowing ourselves up. What do you think about that, and how do you feel about the nuclear freeze movement?

BETHE: I feel good about the nuclear freeze movement. I don't believe that we are in imminent danger of blowing ourselves up, but I do feel that the confrontational stance of the Reagan government has been destructive. They have taken a very hard point of view, always emphasizing the differences between the United States and the Soviet Union instead of emphasizing the common goal of getting nuclear weapons under control. In my opinion, their antagonistic approach has made it more likely that someday there will be a conflict. And if there is an armed conflict, then it may very well lead to the use of nuclear weapons.

Those in Ronald Reagan's administration are really very radical — they call themselves conservatives, but I don't think they are. They have decided to pursue nuclear arms superiority at a huge cost. The freeze movement is simply the natural reaction to such radical nationalism, and I think the movement has worked miracles. Seven of eight initiatives in favor of the freeze won in [1982] state elections, including California, which is the biggest state of the union. And this show of support has modified government policy, though not enough. One well-meaning senator, Claiborne Pell of Rhode Island, recently told me, "Just keep at it. We in the Senate cannot act without knowing that the American people are behind us."

OMNI: Those in the nuclear freeze movement have specifically suggested that the superpowers sit down and negotiate a verifiable freeze on the testing, production, and further deployment of nuclear warheads, missiles, and other delivery systems. What do you think of this proposal?

BETHE: I think the freeze is a very good idea as a first step, giving us time to negotiate. But any viable arms control negotiation takes a long, long time. The SALT [Strategic Arms Limitation Treaty] II treaty, which was very carefully negotiated, took nearly seven years. And at that time, the United States government was entirely behind the negotiator, which is not true now. So a simple, unnegotiated freeze without any complicated verification procedures would be a very good thing. A negotiated freeze with special verification procedures, on the other hand, is not a good idea. It would divert our negotiators from the real problem of reducing armaments way below the present level.

OMNI: What do you think about President Reagan's contention that the Russians will overpower us if we don't keep manufacturing arms at an ever-quickening pace?

BETHE: That is nonsense. The best way to prevent the Russians from getting ahead of us is to ratify the SALT II treaty, which Reagan has refused to do. Our government complains that the Russians have gathered great momentum; that is, that they have built many new weapons in the last five or ten years. Maybe so, but in my opinion, that's best controlled by putting a ceiling on the weapons they can produce. In fact, if we ratified SALT II, the Russians would immediately need to destroy some two hundred missiles.

OMNI: But President Reagan claims the Soviets are far ahead of us in producing countersilo weapons that can wipe out our land-based, intercontinental ballistic missiles [ICBMs]. If we don't produce more ICBMs and countersilo weapons of our own in a hurry, he contends, the Soviets may be able to wipe out much of our nuclear arsenal in a first strike. In fact, he says that by the mid-1980s this "window of vulnerability" will have opened wide enough to give the Soviets a clear advantage in any nuclear war. Are you suggesting that this so-called window of vulnerability doesn't really exist?

BETHE: That's right. All land-based missiles, whether they belong to us or to the Russians, are vulnerable. But only a quarter of our warheads are actually on land-based missiles, whereas the Russians have three quarters of theirs on land-based missiles. Therefore, the Russians are more vulnerable than we are. Furthermore, if the Russians were foolish enough to attack our land-based missiles, we could still retaliate with the main part of our force: airplane bombers, which have little vulnerability because they can take off if there's an alert, and submarine-based missiles, which are not vulnerable at all. These are never mentioned when the government talks about our alleged weakness.

OMNI: Yet the current administration is pushing Congress to fund the MX missile complex, a fourteen-mile-long site that would protect highly accurate ICBMs under a powerful vault of steel and concrete. The President claims an all-out Soviet attack, capable of devastating 90 percent of present-day Minuteman ICBMs, could destroy only 20 percent of the MXs. Even if you don't believe in the window of vulnerability, do you see the MX as having any value?

BETHE: The MX is an abomination. President Reagan has called it the Peacemaker. That's just like calling Robespierre a cure for headaches, and I think that comparison is generous. First of all, my friends say the MX will be very vulnerable, and they give good arguments. As long as its viability is in doubt, we should not build it. Second, I dislike the concept of building more vulnerable missiles to attack the enemy's missiles. Our best security comes from invulnerable weapons. The Russians won't attack our Minutemen, because they know perfectly well that we would shoot back with our submarine-based missiles and our bombers.

OMNI: What do you think about the contention that we can survive a nuclear war?

BETHE: I think it is nonsense. The idea is that we could keep a small-scale, tactical nuclear war at controllable levels. But nearly every military expert will tell you that this is impossible. If we are about to lose at one level, our general in the field would be likely to escalate the conflict to the next level. If the Russians are then about to lose on the next level, they will escalate to a higher level still. And before anybody knows it, a full-scale nuclear war will be raging, full force.

OMNI: Can't anything be done to avoid this doomsday scenario once the bombs start flying?

BETHE: The most important thing is to use the so-called hot line to the Soviet Union. If messages can go across, we might be able to negotiate a settlement or offer to stop the fighting. Senator Henry Jackson of Washington suggested we expand the hot line that exists today: instead of having just one line running from president to premier, we should have additional hookups between generals, senators, and the like. Such communication is especially important in case of an accident. Suppose there is that mad lieutenant in some bunker out in Wyoming who launches one of the Minutemen? We want to be sure we can tell the Russians that this was an accident, and that we are willing to compensate them for it. It is terribly important that the two superpowers do not react wildly.

OMNI: Do you think it's possible that a nuclear war could start as the result of a computer error?

BETHE: It could, especially if those in charge decided to shoot on warning. We have very elaborate early-warning systems aboard satellites that look down on the Soviet Union. Basically, these systems monitor the infrared emitted when missiles are shot outside the atmosphere. Of course, such radiation is released all the time, whenever there's a satellite launching, but those are previously announced, we know about them, and so we don't worry about them. Instead, we look for any sign of twenty to a hundred unexpected launchings in, let's say, one minute. The computers that detect such signals are probably fairly accurate, and infrared radiation cannot be easily falsified. But still, the computer transmission may be in error, informing us of hundreds of launches from known nuclear silos in the Soviet Union — even if not a single launch has actually occurred.

We've already had false alarms as a result of computer errors in our Distant Early Warning system, a radar network that scans northern Canada for approaching Russian airplanes. That system has mistaken the rising moon and even a flock of geese for a plane. Radar, of course, is a wonderful device, but the signals can be confusing.

OMNI: Could a computer error ever launch a missile for real?

BETHE: Computer errors in launches are very, very unlikely, and if such an error were to occur, it would presumably launch a single missile. It's like the mad lieutenant.

OMNI: One hot line call could ease the situation?

BETHE: Yes, the side in error would apologize.

OMNI: In any event, you said that computer errors of any sort would lead to war only if leaders attacked on warning. Is that the policy?

BETHE: It is not, and that is very important. It is a terrible doctrine. But some people have proposed it both in this country and the Soviet Union.

OMNI: Let's say a war does start. Would ordinary civilians be able to protect themselves with the fallout shelters and evacuation plans prescribed by the civil defense program?

BETHE: No. That program is almost totally useless. According to the administration, the program was first suggested, in part, because the Russians have such a program. From my best information, this just isn't so. An important part of any civil defense program would be a drill in evacuating people from a city. If that were ever to happen, we would see it from our satellites. We can see a single person in the open space in Russia — a single person! If there were a hundred thousand people streaming out of some city, we would surely notice that, even if they went on foot. And nothing like that has ever occurred.

But whether the Russians have a program or not, there is a wonderful argument against civil defense: it will not be on time. You can envisage two possibilities. In one, there might be a sudden attack out of the blue. In that case, civil defense is useless, especially against the primary effects of nuclear weapons. In the other possibility, some conventional war may have started in Europe, and I think the chance of that is very, very small. But suppose it occurs and then escalates into a nuclear war. Reagan's proposal is that we might take the precaution of evacuating people from the big American cities to the countryside. In fact, we in Ithaca [site of Cornell] and Tompkins County have been designated as one of the evacuation areas. Our County Council has given exactly the right answer. It has said, "No way. We cannot house these people, and we certainly cannot feed them." There's a further point: if all these people could be evacuated in time, and then sustained in a town like ours, then nothing would be produced in the city. All the manufacturing would be laid still, costing daily about half the gross national product of the country. Under such circumstances, we wouldn't be able to sustain ourselves for any length of time.

One thing that does make sense, though, is teaching people to find protection from fallout in case they haven't been bombed directly. If you want to avoid fallout, going into your basement does make some sense, and going into the basement of a skyscraper makes even more sense. Suppose we're faced with that scenario the Reagan government is so fond of — the Russians attacking our Minutemen. Now, there are few people living near the Minutemen silos, but fallout would extend five hundred miles downwind and would be tremendous. Therefore all the people, and there are a great many of them, in areas five hundred miles downwind should at least know how to protect themselves from fallout. But a major shelter program, as some people have suggested, isn't warranted.

OMNI: Dr. Bethe, in all fairness, the present government has proposed an arms control plan of its own. Would you care to comment?

BETHE: Our government's plan, the so-called START [Strategic Arms Reduction Talks] proposal, is, unfortunately, impossible for the Russians to accept. Reagan's first suggestion, that each side cut the number of nuclear delivery systems more or less in half, is a good idea. But that's only the first part of the proposal. The government has gone further, arguing that only half the warheads of each side be situated on land. That would mean a terrible sacrifice by the Russians, who have naturally stored most of their missiles throughout their vast land mass. They have much less access to the sea than we, so their decision was only logical.

Reagan has also suggested that we not count bombers when equalizing arms, but since we have great superiority in bombers, the Russians cannot accept that either. Nor will they tolerate the suggestion that we inspect each other's nuclear installations on the ground. They have always been very much opposed to any intrusion into their country. Everything is secret there, and military information, of course, is even more secret.

Finally, there is the matter of armaments in Europe. We have been very much troubled by the Russian SS-20, a fairly big, mobile missile threatening all of Western Europe. To counter that, we've begun to install the so-called Pershing II, a group of European-based missiles threatening Russia. That, I think, is a very bad move on our part.

OMNI: Many Europeans are upset at the thought of those missiles within their borders. They feel they'd be more vulnerable than ever to attack.

BETHE: Absolutely. That's the point. That's why we'd be much better off if we based our counterforce aboard submarines stationed off Europe. In fact, the Russians have said they'd cut the number of SS-20s in half if we didn't deploy the Pershing. The proposal is one that I think we should seriously discuss.

OMNI: It seems as if our government's proposals have been built to fail, as if that's really what's desired.

BETHE: I am afraid you may well be right. But we must keep discussion alive, because eventually the government will change.

OMNI: This is all rather depressing. Perhaps we should go back in time to discuss a more positive aspect of the nuclear age. You received a Nobel Prize in 1967 for your work on the nuclear reactions that power the sun and stars. How well has that work held up during the intervening decades?

BETHE: Very well. There are two reactions that power the stars, both of which are propelled by hydrogen. As the reactions proceed, hydrogen gets used up. The sun is now five billion years old, about halfway through its hydrogen life, which is quite satisfactory. But some stars about the size of the sun have come to the end of the hydrogen in their central region. They still have lots of hydrogen outside, but when they come to the end of this central hydrogen, their cores collapse, becoming about five times hotter than they were before. And, paradoxically, the star as a whole expands. That makes it a giant.

Now, one of the most striking proofs of the general idea of nuclear energy production in the stars is the existence of red giants. The details of how a red giant develops — increasing its luminosity, getting cooler and bigger, then shrinking again as the center gets hot enough for helium to react, then expanding again — work out beautifully, in accordance with the general ideas of nuclear reactions.

OMNI: Tell me about these fundamental nuclear reactions.

BETHE: The proton-proton cycle and the carbon cycle both generate energy as protons, or hydrogen nuclei, join to form helium nuclei. In the first type of cycle, the proton-proton cycle, two hydrogen nuclei simply combine directly to form a single helium nucleus. In the second cycle, the carbon cycle, protons collect around the nucleus of a carbon molecule until, finally, a helium nucleus splits off, leaving the original carbon alone once again. And both of these reactions, both of these cycles, produce enormous amounts of energy.

OMNI: You played a major role in developing the understanding of both cycles.

BETHE: Yes, that's true. The proton-proton reaction was really discovered in 1938 in Germany by Carl von Weizsäcker, who has not received enough credit for this discovery and who has received too much credit for discovering the carbon cycle, which is interesting. Nobody mentions him with regard to the proton-proton reaction, and that really was his discovery and his alone.

OMNI: Then what was your discovery?

BETHE: Charles L. Critchfield and I calculated the actual rate at which the proton-proton reaction occurs. Weizsäcker didn't do that. And I was convinced, after that, that this was the reaction. But that didn't fit the big and brilliant stars like Sirius. So, in an attempt to find an explanation for those, I found the carbon cycle. Weizsäcker discovered it at about the same time, but my theory was a lot more complete.

OMNI: You are one of the few people to win a Nobel for work in astrophysics. Why is that so?

BETHE: Well, the Nobel statutes were written in such a way as to make astronomers ineligible. I was the first exception, probably because I was also a pure physicist. The citation first mentions my work on nuclear reactions, and second, my study of the nuclear reactions responsible for the energy in stars.

OMNI: How did you learn of your selection in 1967, and what was your reaction?

BETHE: Because there is no prize for astronomy, I didn't expect it at all. One morning, at six o'clock, I was awakened by a telephone call. Usually a telephone call at that time means a wrong number, so I just let it ring, for about, oh, two minutes. Then I lifted the receiver, and it turned out to be a man from the Swedish TV network, who said, "Well, I am instructed to tell you that you have won the Nobel Prize for physics." Then he read me the citation. He had hardly hung up the receiver when there was another phone call. One after another, all the radio stations around the country called to interview me. By that time I was awake. It happened that my brother-in-law was in the house and in bed, and he decided that war had probably broken out and I was being called from Washington to be told what to do!

OMNI: Did the work that earned you the Nobel also lead to research on controlled nuclear fusion?

BETHE: Certainly. But when I published my work on nuclear reactions in *Reviews of Modern Physics* back in 1936 and 1937, I never thought that engineers and physicists would pick up on it and start thinking about fusion reactions as a new energy source.

OMNI: President Reagan's science adviser, George Keyworth, stated not long ago, "There is no doubt in my mind that fusion will work and will be the ultimate power source in the future." Would you care to comment?

BETHE: I am also optimistic about fusion. At this moment I am not sure that fusion will be used to generate commercial electric power. You want a plant that generates electricity to operate continuously. Yet for the first two decades or so, fusion-power plants may well have frequent interruptions — frequent downtimes. This would be a general feature of any complicated new plant, and a fusion plant will be far more complicated than an ordinary nuclear power plant — a fission plant.

On the other hand, I am very optimistic about the so-called fusion breeder concept. In that technology, neutrons escaping from the initial fusion reaction would combine with uranium-238, an essentially inert material, converting it into highly reactive plutonium. Likewise, the neutrons could combine with thorium, converting it into reactive uranium-233. The plutonium and uranium-233 could then be used to fuel fission reactors [the nuclear reactors in use today]. I do believe that, by the second half of the twenty-first century, this will probably be our most important source of energy.

OMNI: So the fusion breeder would act as an energy multiplier?

BETHE: That's exactly it. The fusion devices that are currently being worked on include the tokamak and the mirror machine. The tokamak is shaped like a torus [doughnut-shaped], and the mirror is a tube with magnets at each end. [Both produce energy much as the sun does. Gas within is heated until it moves violently. The protons and neutrons that make up the gas are then forced to collide, combining to form helium and releasing energy in the process. In the case of a fusion breeder, the moving neutrons would collide with uranium-238 or thorium, producing fissionable plutonium or uranium-233.]

OMNI: The tokamak dominates current fusion research. Do you see more promise, over the long term, in the mirror machines?

BETHE: The tokamak certainly is way ahead of everything else. It has a very convoluted geometry, and so it is quite difficult to operate and maintain and is particularly difficult to use in connection with a breeder. The mirror machine is less advanced. But if it succeeds, I think it is likely that the mirror machine will be a better machine than the tokamak. In any event, either machine is likely to put out only as much energy as it takes to run it — maybe a little more. So using it to produce fuel for a fission reactor would be your best bet.

OMNI: A few years ago William Metz, a staff writer for *Science*, wrote that such a fission-fusion-combined breeder would actually have all the complications of both a fission system and a fusion system and that this would necessarily be an exceptionally difficult way to go. How do you respond to that criticism?

BETHE: I think it is totally wrong. The first idea, it is true, was to surround the fusion device with a blanket of thorium or uranium-238 and make energy in that blanket. This I regard as a bum idea. It combines all the difficulties of both worlds. I want to separate the fission and the fusion completely by operating the fusion breeder off-line from the power plants. And I want the fusion device to make only material that is fissionable and that can then be used in a state-of-the-art fission reactor.

OMNI: You are talking about fusion as a source of cheap neutrons, which would be used to breed cheap plutonium. How do you prevent the plutonium from being used to make nuclear bombs?

BETHE: My idea is that these fusion breeder plants would be very heavily guarded and would be built in special locations. They would not be run by the utilities, which is an important point, but by the government, and the product would then be sold to utilities. The reason that all this is possible is that one such fusion breeder would supply enough fuel for ten to twenty ordinary fission reactors.

Moreover, I would prefer to produce uranium-233 rather than plutonium. None of the high-grade material would ever leave the site. It would be a military site, if you want. It would be subject to that level of security.

OMNI: So by a combination of clever physics and military-type security you would expect to safeguard these materials to prevent their misuse? In other words, have your cake and eat it, too?

BETHE: Exactly. Besides, we have tons of weapons-grade material — in the form of weapons. These are far more convenient for a terrorist to steal than just the material, and we have continued to safeguard them successfully.

OMNI: In 1974, using a Canadian-supplied reactor, India built a bomb — something India was not supposed to be able to do. Would these safeguards be sufficient to prevent anything like that from ever happening again?

BETHE: What happened in India probably will occur again. It is very difficult to prevent completely any accumulation of fissionable material for illicit purposes — that is, for making bombs. All we can hope to do is keep the amounts of material that are so diverted very small so that they don't make very much difference in the world picture.

OMNI: In other countries, such as France, Japan, perhaps the United Kingdom, certainly the Soviet Union, nuclear power is being developed rapidly. Here at home, though, that development is being held back. Why should this be?

BETHE: The reason is economics and the availability of material. We have coal, lots of coal, and it is cheap. The price of coal is still less than $40 a ton here in the United States. In Germany, it's $120 per ton. The Germans and the British like to use their own coal, but there is very little of it, and it is tremendously expensive. For those two countries, the cost of making electricity from coal imported from the United States is about the same as the cost of making it from fission.

OMNI: Isn't it true that South Africa, which has abundant and particularly cheap coal, is building nuclear power plants?

BETHE: I am afraid I have to attribute nefarious intentions to the South Africans. I believe that they are very much interested in nuclear weapons, not only in nuclear power. So that country's a special case.

OMNI: We actually have two classes of nuclear reactors in common use in this country. Far less well known than the power plants with their cooling towers, which one sees on the nightly news, are the nuclear plants used in naval submarines and other vessels. How would you compare the safety and performance record of the naval reactors with the civilian ones?

BETHE: We do know that no submarine ever blew up because the reactor malfunctioned. I think we know that there has not been a meltdown accident in a submarine — probably not even a partial one. The submarine reactors have extremely good quality control, in every detail. And the navy is willing to pay very high prices for these reactors. In my opinion, quality control — excellent quality control — should also apply to the civilian reactors. And I feel that this could be improved. The regulatory climate should shift in the direction of improving quality control.

OMNI: Do you believe that, for the sake of quality control, the navy pays relatively more per installed kilowatt than civilian plants do?

BETHE: I am sure they pay much, much more than civilians.

OMNI: So then, in order to meet economic criteria, civilian plants must necessarily pay somewhat less attention to quality control than the navy does.

BETHE: Probably somewhat less, that's true. But civilian power plants have one great advantage. They are big. Because they are big, the cost per kilowatt will automatically be less, even with the same amount of quality control. The typical naval reactor is maybe fifty megawatts and the typical civilian reactor is a thousand.

Now, I have high hopes for INPO — the Institute for Nuclear Power Operation — an organization created by the nuclear industry after the Three Mile Island accident. One of its several functions is to supervise the building of nuclear reactors. Another is to look after the safe operation of nuclear power plants. And I think that's an extremely important point. Some utilities are very good, and some are not so good. INPO is trying to raise the quality of operation by giving information to all the individual utilities, and also by having its own people go around to see whether the operations are completely up to standard. So in a way they constitute a second Nuclear Regulatory Commission.

OMNI: In Germany the Atomgesetz — the Atom Law — requires that safety take precedence over all other considerations, even economic considerations, and that no effort be spared in order to ensure that safety has been pushed to the limit. If we adopted such a law in this country, would that influence the choice between light-water versus far safer gas-cooled reactors?

BETHE: I think it probably would. I think it's a stupid law. It could greatly force up, even double, the cost of our energy. And that could begin to be intolerable.

OMNI: You obviously have a rather different view of reactor safety from that of many other influential people. Why do you feel as you do?

BETHE: Because I consider safety to be a matter of numbers. I consider everything to be a matter of numbers. The question is, what are you likely to buy with further increases in safety? At current safety levels in our nuclear industry, I anticipate an average of two fatalities per year. A major accident, which has not happened, might occur once in a thousand years. I define a major accident as one in which large amounts of radioactivity are vented on the public. In such an accident the estimate — and I think it a very sensible and good estimate — is that a thousand people would die from delayed cancers. Of course, it's not certain at all that anybody would die from delayed cancers. But going by present assumptions, that's a thousand deaths every thousand years. That's one a year.

I add to this the possibility that such a major accident could occasionally be coupled with very bad wind and rain conditions, which would increase the number of fatalities, because some of the radioactivity might fall out very close to a populated area. This is all in the Rasmussen Report [a 1975 study on nuclear safety]. For that reason I double the rate. That's two per year.

OMNI: For how many reactors is that?

BETHE: For a hundred reactors, for a thousand years.

OMNI: So if we had a thousand reactors, we could expect twenty deaths per year, on the average.

BETHE: Twenty fatalities per year. Compare this with the statistics on drunken driving. Half of all our traffic deaths are due to drunken driving. We could reduce the number of deaths caused by auto accidents by twenty thousand per year if we were absolutely rigorous in preventing drunk driving. But in our society we tolerate this; we don't lift the licenses of drunk drivers or put them in jail.

OMNI: What would you say then about the attitudes of antinuclear activists who cite the safety issue?

BETHE: I think they are confused. There was an article in the February 1982 issue of *Scientific American* that ranked a long list of risks that cause fatalities, ranging from smoking, alcohol, and automobiles at the top to power mowers and high school football at the bottom. And nuclear power ranked just above high school football and a little below commercial aviation, which, as we all know, is very safe. And the author has still overestimated the danger of nuclear power, probably by a factor of ten.

That article also contained a list ranking the perceived risks as reported by a poll of college students and of members of one chapter of the League of Women Voters. And nuclear power was right at the top — more dangerous than handguns, more dangerous than autos or smoking. Now the League of Women Voters are well-meaning people, and on many political issues they are extremely sound. But in their estimate of the dangers of nuclear power, they are just totally off the mark. They are not extremists in any way; they are simply confused.

OMNI: Do you think public opinion will change in this respect?

BETHE: Yes, I think so. And then the nuclear industry will be able to move ahead.

OMNI: If that happens, we may wind up with a great deal of electric power — even a surplus of electricity. Some people have proposed that surplus electricity could be used to produce hydrogen as a replacement for natural gas and perhaps even for automotive gasoline.

BETHE: Certainly natural gas will be the first thing to be replaced. I am rather optimistic that our natural gas will last a considerable time — much longer than oil, certainly much longer than domestic oil. But ultimately it'll have to be replaced. Hydrogen certainly is a very sensible replacement. The question is one of safety. People assure me that hydrogen can be transported and used as safely as natural gas. I don't know how well founded this assurance is. It may be entirely right, and in that case we will get to the hydrogen economy some time.

OMNI: You hold out more hope for nuclear than for fossil fuels. Could you comment on synthetic fuels?

BETHE: There are two energy problems. One is getting enough total energy, which we can obtain from nuclear power or coal, and the other is getting enough liquid fuels. We cannot drive our automobiles with electricity — at least, not very well. We cannot run our airplanes with electricity, and I think that will remain true for a long, long time. We need liquid fuels for that. And I strongly believe that oil will run out, in spite of the current glut. So I think we are going to need synthetic fuels.

OMNI: One final question, Dr. Bethe. What kind of work in astrophysics do you think would suffice to win another Nobel Prize?

BETHE: Perhaps if someone could more definitely prove theories about the formation of galaxies and stars and about cosmology; that might do it. But for me, I think one is enough.