

# ATOMS FOR PEACE + 50

## Nuclear Energy & Science for the 21st Century

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**Beyond the Nucleus: Matter, Energy, Space and Time**

**Panel Chairman:**

**Dr. Raymond L. Orbach**, Director, Office of Science, Department of Energy

**ORBACH:** The next speaker will talk on the development of high-energy physics. Dr. Jonathan A. Bagger is the Krieger-Eisenhower Professor from the Department of Physics and Astronomy at Johns Hopkins University. He is also a General Councilor of the American Physical Society, a fellow of the APS, and a member of the Fermilab Board of Overseers. He serves on the editorial boards of the Johns Hopkins University Press as well as Physics Reports, the Physical Review, and the Journal of High Energy Physics.

He's twice been a member of the Institute for Advanced Study at Princeton. He's held a Sloan Foundation Fellowship and an NSF Presidential Young Investigator Award. And, indeed, he served on three HEPAP sub-panels, several NSF advisory panels, the Stanford Linear Accelerator Center Scientific Policy Committee and was Chair of the Division of Particles and Fields of the American Physical Society. From '86 to '89 he was Associate Professor at Harvard University and prior to that a post-doctoral research associate at SLAC. He holds an A.B. from Dartmouth College and a Ph.D. from Princeton University. His research interests center on high-energy physics at the interface of theory and experiment. He was co-chair of the HEPAP sub-panel that developed the long-range plan for the United States high-energy physics, "The Science Ahead, the Way to Discovery." His talk is titled, "Beyond the Nucleus: Matter, Energy, Space, and Time." Jonathan.

**BAGGER:** Thank you very much. It is an honor and a privilege to be here today, celebrating the 50th anniversary of President Eisenhower's speech before the United Nations. From the beginning, the Atom-for-Peace movement was closely tied to nuclear and particle physics. Today, I will tell you part of that story, as seen from the eyes of a physicist.

But first, let us think back to 1953, the year of President Eisenhower's speech. The world was coming off a terrible period of two world wars, a Korean war, and a great depression. Nevertheless, the first half of the century was also a period of tremendous progress for humankind – progress that came from harnessing the power of science. Much of that progress came from chemistry, based on the periodic table of the elements.

During the first half of the century, scientists had come to understand the periodic table in terms of atoms and nuclei, composed of protons, neutrons, and electrons. At the time, protons, neutrons, and electrons were the only elementary particles – together with a few oddballs – the pions, kaons and muons that were only seen in cosmic rays.

But 1953 was a watershed year for particle physics. It marked the start of the Brookhaven Cosmotron, a 3.3 GeV proton accelerator that could recreate – in a controlled setting – the physics of the cosmic rays. The Cosmotron was a particle accelerator that smashed protons into stationary targets, creating new particles via Einstein's famous equation,  $E=mc^2$ . The properties of these particles could be carefully measured and their origins understood.

The Cosmotron and its successors, from the Berkeley Bevatron to the Fermilab Tevatron, were successful beyond anyone's wildest dreams. These accelerators unleashed a torrent of discovery over the next half-century.

The 1950's were the decade of a great unraveling, as Ray said, when the tidy picture of protons, neutrons and electrons came apart at the seams. Accelerators produced many hundreds of new and "elementary" particles, siblings of protons, neutrons, pions and muons.

By the 1960's, physicists were searching the data for patterns and symmetries, trying to find order in the chaos. Early in the decade, quarks were proposed as a mathematical device for classifying the new particles. Only later, in 1969, in a famous experiment at SLAC, did it become clear that quarks are real – and that protons and neutrons are not elementary, but composed of quarks.

In the 1970's and 1980's, new accelerators discovered new quarks, together with the forces that link them. Piece by piece, a new periodic table was constructed, encoding our knowledge of the subatomic world. Three out of four particles in the table were discovered in the Atoms-for-Peace era.

The international nature of the field is reflected in the fact that the quarks, the leptons, and the forces that link them were discovered in laboratories across the country and around the world. They were discovered at Brookhaven, SLAC and Fermilab – and at Savannah River – all DOE laboratories – as well as at CERN in Geneva, Switzerland, and DESY in Hamburg, Germany.

The new periodic table contains six quarks and six leptons, partners of the electron. Protons and neutrons are composed of up and down quarks. The quarks range in mass from millions of electron volts to billions of electron volts, with the top quark weighing in at 175 GeV, as much as an atom of gold. The leptons range in mass from a fraction of a single electron volt, to more than a million electron volts. The quarks and leptons interact via four forces, also carried by particles.

The final pieces fell into place in the 1990's. The top quark was discovered at the Fermilab Tevatron, a four-mile-long accelerator more than 1,000 times more powerful than the Cosmotron. The Tevatron is a technological tour-de-force. It accelerates protons and antiprotons – matter and antimatter – to near the speed of light, and then collides them head-on-head in beams of particles thinner than a human hair.

The results of the collisions are recorded in particle detectors and analyzed by teams of physicists from around the globe. In fact, true to the spirit of Atoms-for-Peace, almost half the physicists using the Tevatron are from foreign countries. They bring resources from their countries to the United States, all in the pursuit of science.

So today, where do we stand, after these 50 years? I believe that we stand at a crossroads in the history of science.

- First and foremost, we have a new periodic table of subatomic physics, along with a precise and quantitative knowledge of how the pieces fit together. History will record this as one of the crowning achievements of 20th century science.

- Beyond that, we have advances in technological development that affect us all.

- o Today, there are over 15,000 particle accelerators in the world, contributing to medicine, materials science, environmental science and even biology.

- o Particle detection techniques are essential to the fast-moving field of medical diagnostics.

- o The world-wide web was invented by particle physicists and given to the world – to facilitate communication and coordination of far-flung collaborations.

I know first hand that particle physics provides big ideas that pull young people into science. Such technically trained students are essential for economic security and national defense.

The advances of the last 50 years have brought us to the point where we can ask bold new questions about the structure of matter, energy, space and time. Without doubt, we have a firm foundation for the science ahead. We can look forward, in the words of Keats, “.... like stout Cortez, when with eagle eyes // He star'd at the Pacific – and all his men // Look'd at each other with a wild surmise – // Silent, upon a peak in Darien.”

For example, we know that the two pillars of twentieth century physics – quantum mechanics and Einstein's relativity – are inconsistent with each other. The only known resolution is string theory, in which the elementary particles are nothing but the vibrations of tiny strings. String theory, though, requires that we live in more than four spacetime dimensions. The discovery of extra dimensions would be an epochal event in human history.

Where are the extra dimensions? How many are there? How are they hidden? What are their shapes and sizes? Such questions are moving from science fiction to science fact.

Cosmology provides another example: During the last 50 years, particle physics and cosmology have grown increasingly intertwined. As we look at the cosmos, we look back in time, to an earlier epoch – before planets, before stars, before atoms, and even before nuclei, back to a time when the Universe itself was a soup of quarks and leptons. To understand our Universe, we need to understand the physics of its most basic ingredients.

Today, as we gaze at the cosmos, we glimpse the future of particle physics. Cosmologists tell us that most of the energy in the Universe is dark: Dark Matter and Dark Energy. Dark Matter is like ordinary matter in that its gravitational interactions pull the Universe together. Dark Energy is something else entirely. It's like antigravity, in that its gravitational interactions blast the universe apart.

What are the Dark Matter and Dark Energy? They are not in the periodic table of quarks and leptons.

Dark Matter most likely consists of stable new particles with weak interactions and masses of about 1,000 GeV. Such particles, streaming through the Universe, left over from the Big Bang, have just the right properties to account for the cosmological observations. Dark Energy, on the other hand, is a total mystery. It is related to the energy of space itself....

Cosmological observations tell us that the Universe is 4% quarks and leptons, 23% Dark Matter, and 73% Dark Energy. I find this humbling: the stuff that we are made of is but a tiny part of the Universe. I find it exciting to know that most of the Universe is composed of a new form of energy, unlike anything we have seen to date.

To quote the famous cosmologist William Shakespeare, in Hamlet, “There are more things in heaven and earth, Horatio, // Than are dreamt of in your philosophy.”

What are the Dark Matter and Dark Energy? These questions will drive particle physics for the next 50 years. As we tease out this thread, who knows what we will find. But these questions seem to me to be completely within the mission of the Department of Energy – and ripe for exploration, in partnership with NSF, NASA, and the world community.

The first step towards exposing the dark side of the Universe is to characterize the Dark Matter. Astrophysicists have proven that it exists, and they are trying to observe the Dark Matter particles as they stream through detectors here on Earth. But what we really need is to produce Dark Matter and measure its properties in laboratories here on Earth. That requires accelerators with the energy necessary to produce the particles – just like 50 years ago, when the Brookhaven Cosmotron began to unravel the story behind the cosmic rays.

Astronomers use radiation of different wavelengths to observe the Universe. So too do particle physicists use different probes. To characterize the Dark Matter, they need proton and electron accelerators, working in tandem, each revealing part of the picture.

The proton side of the equation is covered by the CERN LHC. Come 2007, the LHC, located in Geneva Switzerland, will become the world's highest-energy accelerator. With a power almost

ten times that of the Fermilab Tevatron, the LHC will provide a first glimpse of this new landscape. Although primarily a European machine, the LHC was constructed with important assistance, both financial and technological, from American physicists. Indeed, almost 20% of the LHC users are American.

The electron side requires a Linear Collider. A series of studies – in Europe, Asia, and the United States – has concluded that a Linear Collider is essential to characterize the Dark Matter that pervades the Universe. In this sense, the Linear Collider is the true Dark Matter Microscope, necessary to resolve this new type of matter.

The Linear Collider is the first fully international project in particle physics. Scientists from each region have committed themselves to work on the machine – wherever in the world it is built. They are working together to refine its design.

The machine is of such a scale that the resources – both human and financial – require the full commitment of the world community – in the best spirit of Atoms for Peace.

In 1953, President Eisenhower faced a budget deficit and a tense international arena. In spite of that – or perhaps even because of it – he committed the United States to the Atoms for Peace program. “I know that the American people share my deep belief that if a danger exists in the world, it is a danger shared by all; and equally, that if hope exists in the mind of one nation, that hope should be shared by all. ... [The] United States pledges before you ... to devote its entire heart and mind to finding the way by which the miraculous inventiveness of man shall not be dedicated to his death, but consecrated to his life.”

The Atoms-for-Peace movement led, in 1954, to the establishment of CERN, the European particle physics laboratory, an organization that now leads the world in particle physics – and has helped knit together the European continent for 50 years.

Even today, the Atoms-for-Peace ideal is reflected in the flags of the nations that work at Fermilab. It transcends regional conflict, through projects like the recent string theory conference in Teheran, and the Middle Eastern Light Source, SESAME, in Jordan, whose founding states include Bahrain, Egypt, Iran, Israel, Jordan, Pakistan, Palestinian Authority, Turkey, and United Arab Emirates. Where else but physics could these nations meet on common ground?

It is my fervent hope that, after today, the United States will recommit itself to the ideals of Atoms for Peace. From Lewis and Clark to Shepard and Glenn, the United States has been at the forefront of scientific exploration. Today, scientific leadership requires resources, to be sure, but it also requires the political will to help scientists create the structures necessary to do their job.

I believe that particle physics represents one of the most successful areas of international cooperation. From the pivotal role of CERN in postwar Europe to the global collaborations of today, particle physicists have a history of working together with great success. Even today, physicists designing on the Linear Collider are breaking new ground in international partnership.

At the beginning of the last century, few understood how scientific research would fundamentally change the world. But continued and consistent investments in science helped make the United States what it is today. As we head into the new millennium, few doubt that scientific research will remake our world yet again. It is our choice whether we want to help make this world – or retreat from it. I think the choice is clear. Thank you.

[applause]

**Questions and Answers:**

**ORBACH:** The floor is now open for questions.

**KRISCH:** My name is Alan Krisch. I'm a physics professor at the University of Michigan. One important benefit of the Atoms for Peace proposal was the start of exchange visits between Russian and American scientists and students, especially in high-energy and nuclear physics. This seemed an excellent and successful example of what Susan Eisenhower this morning mentioned as her father's hope that the Atoms for Peace program would build good relations between scientists and students who would later become scientific leaders and help to have better relations between the two sides of the Iron Curtain. I think this worked.

I've been involved in this program since the late 1960s. Unfortunately, this mutually beneficial exchange was significantly reduced when the now expired "Department of Energy / Minatom Peaceful Use of Atomic Energy Memorandum of Cooperation" was not signed when it was expired in February, 2002. Has any progress been made in getting this signed again so this can continue?

**ORBACH:** I think the question was addressed at me and not the panel. Would any members of the panel like to respond to that? [laughter] Yes, there is progress and, in fact, in today's newspaper you will see one of the reasons why that progress will now accelerate. Thank you.

Are there other questions addressed to the panel? Yes.

**GERKY:** Bob Gerky, INNEL, to one of the three panelists. We've heard a lot about, where did the water come from on Earth? And I'd be curious as to what the latest thinking is. There are some who have said the water on Earth has come from comets. Does that hold any water?

**ORBACH:** Michael?

**TURNER:** I'm looking for an astronomer or planetary scientist on my left side here but I don't see one. Well, it certainly came from the quarks [laughter] in the Big Bang and it went through the Big Bang nucleosynthesis. I cannot tell you what the best idea for where the water on Earth came from. I can only tell you the early origin of water, which is extremely exciting.

\_\_\_: Is there any reason that it should have come from any different place than all the rest of the elements that we have here on Earth?

**TURNER:** Well, chemistry plays an important role in the formation of the solar system because some of the elements are more volatile than other elements. So, here on Earth we don't see the primordial mix. Most of the atoms in the universe are hydrogen. We certainly don't see that here on Earth. But the Earth's gravity isn't strong enough to hold the hydrogen and the helium, whereas in the sun and in the giant planets it's possible. So, chemistry plays a very important role in what we see here.

**ORBACH:** Questions? As Chairman, then, I am going to take the liberty of asking my own, which has been driving me nuts for five years. I would like to ask the panel to speculate on just what this dark energy is.

**TURNER:** Well, I think my son's idea is pretty good.

**ORBACH:** Are we really that bereft of ideas?

**TURNER:** No, I think we are at the phase right now where we need a really crazy idea. One of the exciting things about science is that when you get the very toughest problems, they involve some creative break, thinking outside of the box. So I tell this to graduate students and undergraduates – and I also put a footnote saying, “Not every crazy idea is a solution to a profound problem. Some of them are just crazy ideas.”

The range of things that we're thinking about start with something as mundane as the energy of the quantum vacuum. The problem there is that Jonathan and his friends can't calculate how much the quantum vacuum weighs. When they try to calculate it they get an absurdly large number before they say it must be zero.

[Laughter] It could also be a milder form of inflation. And an idea that I really, really like, because it seems crazy enough to be correct, is that there is no dark energy; we just don't understand gravity. And that theme, again, that Jonathan was talking about, was that this marriage between gravity and quantum mechanics will require a modification of general relativity. If you'd asked Jonathan and his colleagues five years ago where that modification would be, they would have said, “Oh, it is going to be at very, very short distances. It's not going to affect the cosmos.”

But you never know where the clues are going to come from and this could be the clue that tells us about how we have to modify general relativity. And so I think that the solution to this problem is not that we go back and look at Jonathan's paper and find in page five that there is a two that should have been a 1.5. I think it's that we find something out very profound about matter, space, time and energy.

**BAGGER:** Mike is completely right about that. I displayed a graph, which showed quarks and leptons and so forth, but that was really just a schematic for a whole structure that allows you to do calculations that are tested at experiments to better than a tenth of a percent level. And that whole structure completely breaks down on the subject of dark energy. As Mike was saying, if you use that, basically, you find that the dark energy should be infinite – and in particle theory if it is infinite, well, maybe it's zero; you missed something.

The fact that it's not zero and it's not infinite, is something that is just completely beyond anything that we can understand and so something brand new has to happen and we just don't have a clue what it is.

**ORBACH:** Are there other questions?

\_\_\_: Well, it is sort of a comment. I'm an experimenter so I don't really believe much of anything that can't be measured. There was an article in Scientific American within the last year and I'm bad with names so I forget the guy's name but he proposed a good solution would be to have a very small extra term to Newton's Law that deviates from it at large distances. As far as I know there is no direct experiment that shows that you can't have something which would only cause deviations from Newton's Law nearby.

And a bunch of my theory colleagues dumped on me and started explaining why that couldn't work but I think it is something to look at.

**BAGGER:** The problem is that the violence you have to do to the theory must be consistent with a suite of precision measurements that have been made so far. And that imposes constraints. You have to be consistent. Yet, I agree. The answer has got to be crazy. There is not much wiggle room – but there is a hole somewhere and we have to find it.

**ORBACH:** I think one has to be careful of empirical fits. I mean you can play games with the laws – but why? – was my response when I read the article. It was certainly a clever argument but it doesn't answer anything. In the same way that the cosmological constant can change the sign and give you expansion, yet it doesn't tell you where it comes from and that is what these gentlemen have been struggling with. But you actually said something, Michael, that was quite, and, again, Jonathan, quite extraordinary. You believe that the structure of general relativity may be inaccurate.

**TURNER:** Well, certainly in science we know that at any given point in time, our description of the natural world is just an approximation and what's exciting about the scientific process is that it is never over. Newton wasn't wrong; he just didn't get the whole story. In science successive theories eat their predecessors whole if we are doing our job right. And so, Einstein just didn't get the whole story. He got a big, big, chunk that we're still trying to swallow. We're still trying to understand black holes and their meaning and we're still trying to understand the Big Bang.

But I think if you took a poll among physicists, I think most of us would say, Einstein didn't get it all. He did not have the last word on gravity and we have more to learn and we're looking for clues and maybe the cosmic speed-up is a clue to tell us which direction to go.

**BAGGER:** Also it's quite possible that the cosmological constant is related to extra dimensions, because then it's a question of how our four-dimensional world is embedded in a higher dimensional space. Again, we don't know.

**ORBACH:** In the spirit of experiment, can you give us some clues as to how these extra dimensions might actually be observed?

**BAGGER:** Well, in particle physics, everything shows up as a particle. So, actually, if they are the right size, the extra dimensions could be seen as a set of new particles at new accelerators like the LHC, or they could be seen through deviations from Newton's Laws using table-top experiments, depending on the type of new dimensions we are talking about. They might be so small that they are only seen indirectly here or there. We don't know.

Previously, people thought that these extra dimensions had to be so small that, well, you basically couldn't see them. But recently theorists have figured out how they can be infinitely large and you still won't know that they're there. And so the story is wide, wide open.

**ORBACH:** Further questions? Yes.

**DOWNEY:** Jim Downey, again, at Harvard. And I would have to say I'm not much of a string theorist except for when it involves tying my shoes. My question is a follow-on to that. It seems from what I have read about string theory that one of the flaws is that it's heavy on the word theory and that experiments to validate it are extremely limited. I'm wondering if we have to find multiple universes or if we can be comfortable at some point with the fact that this may, in fact, be the only universe that ever was.

**BAGGER:** String theory is, at this point, so early in its development that one can't even say, really, what it predicts. How it connects to experiments, we don't know. It's more of also a paradigm at this point, than an actual precise theory with predictions. We'll have to see. Time will tell how it fits in, how it is detected, if it's detected.

**TURNER:** To comment on your multi-verse possibility, I think what intrigues people are the questions that string theory addresses and the mathematical beauty. Then if you marry string theory with this idea of inflation that I was talking about, you could have had multiple Big Bangs and the rules, what we call the laws of physics, the local bylaws of physics, could be different in the different inflationary events and so the universe could have a structure that is infinitely larger than we can imagine. If this is so, this would be a breakthrough on the same level of Copernicus, getting us out of the center of the universe and the idea that there a multi-verse structure would bring us back down to Earth.

As you say, we can't test that yet. So it's this intriguing idea because the hallmark of science is testability. And so I think you even find string theorists who are desperate to find little ways to test the theory because you have to test these ideas in science.

**BAGGER:** Is that idea just giving up? There are billions of universes and this one is the way it is just because it is? Are we giving up to say that?

**TURNER:** Well, you're talking about the anthropic principle, which I'm not a fan of—

**BAGGER:** Well, it's related to what you are saying.

**TURNER:** If the universe has this multi-universe structure that you asked about, and we're very far from saying that, then it's a fact of nature that we have to accept. So, let's wait and see if we have to accept that fact.

**ORBACH:** There's a book by Martin Rees called *The Six Numbers that Determine the Universe*, which raises this question, pointing out that these six numbers, which are the cause for existence, are accurate to an incredible limit for us to exist. And, therefore, why those six, which forms the basis for the second book that he wrote, and I refer you to that.

**RICHTER:** Burt Richter from Stanford. The whole history of physics is the history of metaphysics turning into physics because of experiments. And right now what we are suffering from is a dearth of experiments because the experiments are getting more complicated, bigger, and more expensive. My poor theory colleagues don't have any data to anchor them and so they are floating in the ether – multi-verses and strings and all the rest of that sort of thing.

But sitting up there is one person controlling the budget of the Department of Energy, another person controlling the budget in certain areas of the National Science Foundation and what we've got coming along now are not only things like the LHC, this great accelerator, but we're going to have new telescopes, we're going to have new X-ray satellites. And I think in the next ten or 15 years, I wish it were faster, we're going to have some new facts and new facts are going to bring some of my theory friends back from floating around in the ether to having to make contact, once again, with the real world and then we're going to start to move to a new concept.

**TURNER:** I hate to dispute. I hate to disagree with Burt Richter. You're absolutely right. We have wonderful possibilities in front of us and we have a plate that is very, very full and we will have a hard time getting everything done. But I think what's very exciting in this connection between the quarks and the cosmos, is that this astronomical fact that the universe is speeding up is not just of interest to astronomers but it's of great interest, as you well know, to your theorists.

Maybe it's not the clue that they wanted. Maybe they wanted the Higgs particle first, but science is always disorderly and so we've got other clues coming in, the dark matter, the dark energy. But I take your point on the possibilities before us and finding a way to carry out the experiments and realize our dreams.

**ORBACH:** I'm going to have Rob Goldston ask the last question.

**GOLDSTON:** Some areas of particle physics are deferring from making predictions yet and there are these 17 or 19, depending on how you want to count them, basic numbers that are behind the standard theory. We had Roger Penrose come to Princeton and he took the occasion to go after string theory as being irrelevant. That was kind of an interesting experience at Princeton. But I asked him this question and his answer – And I'm curious what your answer is – Since we can't have a prediction, how about a meta-prediction, so to speak, a prediction about the predictions. When will one of these numbers come out of string theory? The first one?

[pause]

**ORBACH:** Would you like me to predict when Jonathan will answer this question? [laughter]

**GOLDSTON:** So to speak, a meta, meta-prediction.

**BAGGER:** To be honest, I'm not a string theorist. So I'm backpedaling fast. I actually believe in effective field theory. I'm more like a condensed matter physicist, mucking around with my effective Hamiltonian that describes the standard model. I can use it to see great things coming with the next factor ten in energy. But to get all the way to the string theory scale is more than I can imagine. Nevertheless, I can use string theory for inspiration and take the big picture of string theory and use it as a guide. To do detailed calculations, that's like trying to derive chemistry from quarks and leptons. There are many steps in between. It will be very hard.

**ORBACH:** As one of those guys who mucks around with materials, let me thank the members of the panel and all of you in the audience. I think Burt Richter's plea, that this will come faster than 15 years, is upon us. We have four to five more years of operation of Fermilab. These issues, these new particles, the experiments that have been called for may well emerge from that. One has, as you saw, the large hadron collider at CERN, and the possibility of the linear collider in parallel. We have in front of us machines and theories that address the very fundamentals of our existence. It's an exciting time to be alive and I thank you all for joining us this afternoon.

[applause]

**END OF SESSION 4**