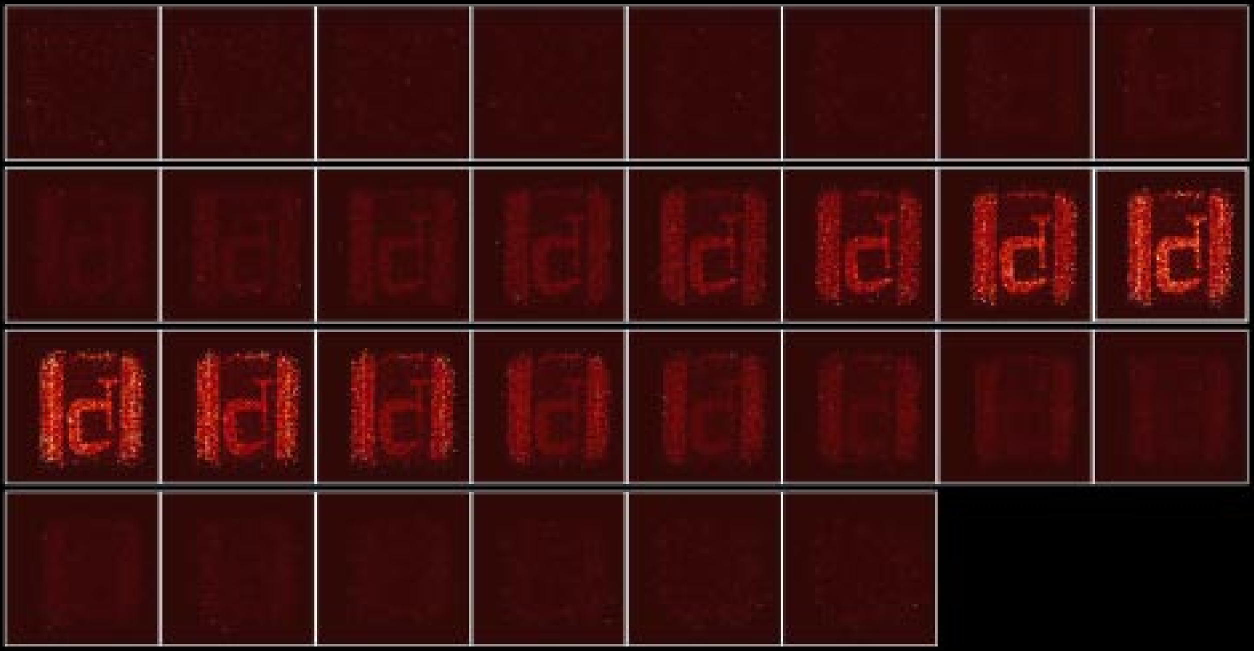
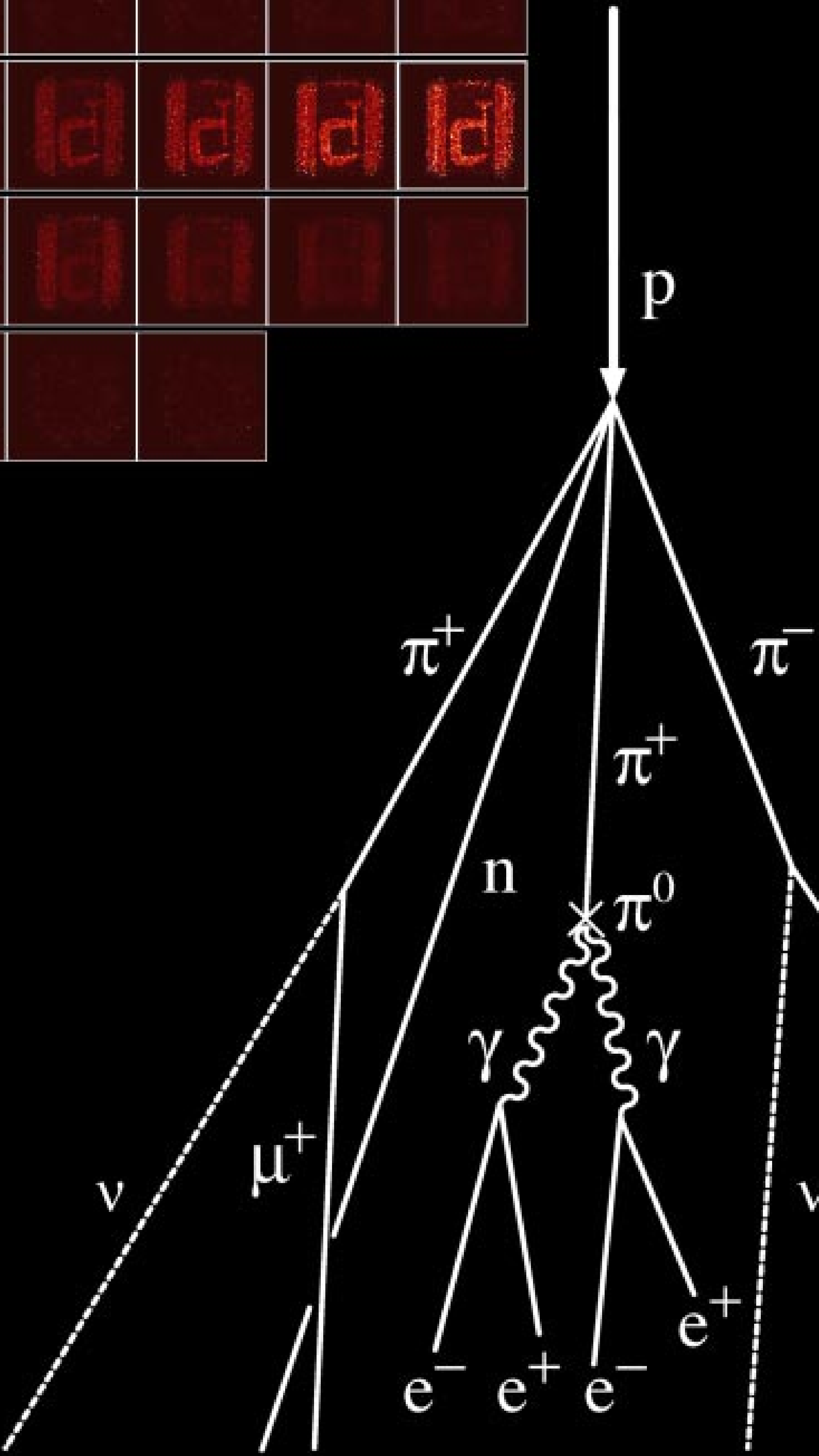


Cosmic rays are mostly protons from outer space that have kinetic energies as high as that of an apple falling a few meters in Earth's gravitational field. When a cosmic-ray proton strikes an air molecule—typically at an altitude of about 15 kilometers—the result is a shower of energetic particles and radiation. Because the muons produced move at close to the speed of light, their short lifetimes (2.1 microseconds) are extended by the time dilation effect of special relativity, which allows most of them to reach Earth's surface without decaying.

p — proton
n — neutron
π^+, π^-, π^0 — pions
μ^+, μ^- — muons
e^- — electron
e^+ — positron
ν — neutrino
γ — gamma ray

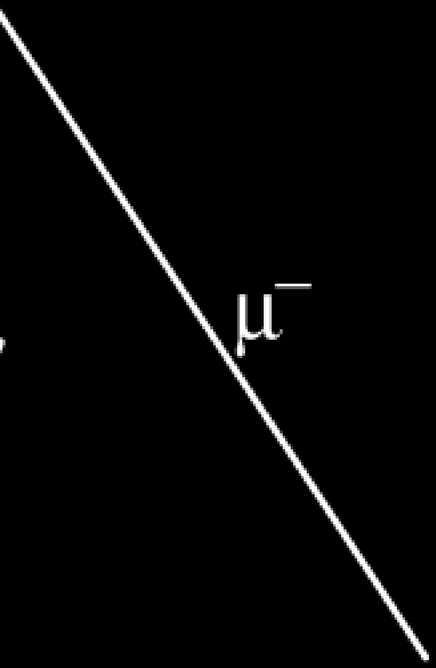


Muon Radiography

Detecting Nuclear Contraband

by Brian Fishbine

Muons, elementary particles that shower down on Earth, hold promise as a sensitive means of detecting nuclear materials being smuggled into the country.



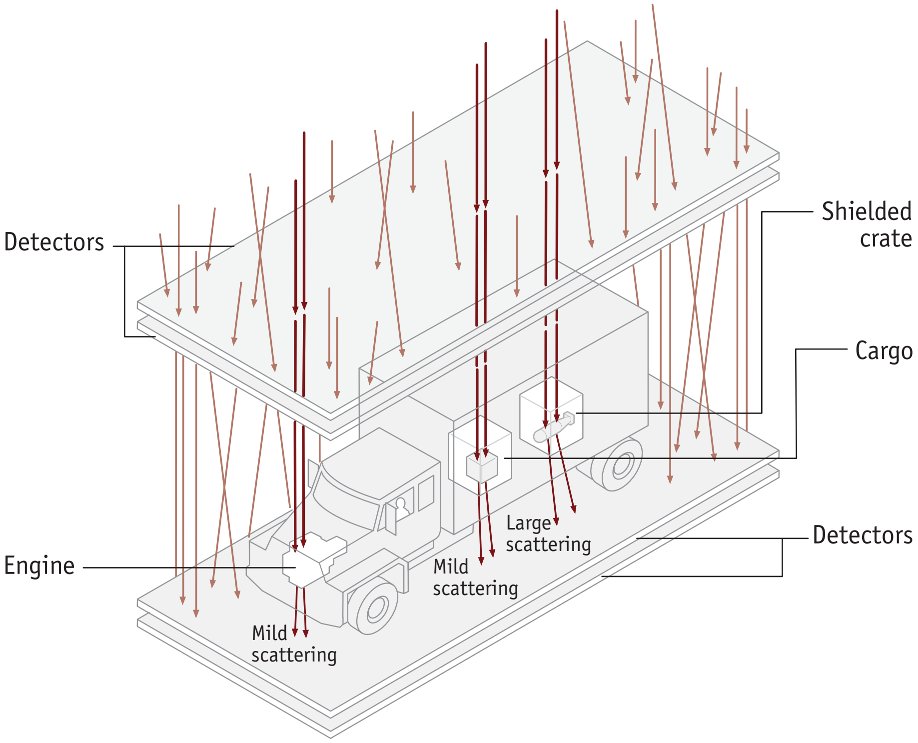
Each minute, about 10,000 muons rain down on every square meter of Earth. These charged subatomic particles are produced when cosmic rays strike air molecules in the upper atmosphere. The cosmic rays themselves are mostly energetic protons produced by the sun, our galaxy, and probably supernova explosions throughout the universe. Thousands of muons pass through us every minute, but they deposit little energy in our bodies and thus make up only a few percent of our natural radiation exposure.

A team of Los Alamos scientists—Konstantin Borozdin, Gary Hogan, Chris Morris, Bill Priedhorsky, Andy Saunders, Larry Schultz, Margaret Teasdale, John Gomez, and Val Armijo—has found a promising way to use this natural source of radiation to detect terrorist attempts to smuggle uranium or plutonium into the country. Either nuclear material could be used to make an atomic bomb (see sidebar on page 16). The technique also detects lead and tungsten, which could be used to shield the gamma rays emitted by nuclear materials—or other radioactive materials—in order to elude detection.

The new technique uses the fact that muons are more strongly deflected, or scattered, by nuclear or gamma-ray-shielding materials than they are by materials such as plastic, glass, and aluminum. This enhanced deflection occurs mainly because the atomic nuclei of nuclear and gamma-ray-shielding materials contain large numbers of protons, which exert large electrostatic forces on muons passing nearby. Since the number of protons is given by the atomic number *Z*, such materials are called “high-*Z*” materials.

Center for Homeland Security

The Laboratory recently established a Center for Homeland Security to coordinate interactions with the new Department of Homeland Security. The Center has four major focus areas: chemical/biological threat reduction, radiological/nuclear threat reduction, critical infrastructure protection, and national infrastructure simulation and analysis. Los Alamos efforts to enhance homeland security have already made significant impacts—from helping identify the strain of anthrax used in the attacks just after September 11 to developing computer simulations that help policymakers assess the vulnerabilities our nation's infrastructures, including public health. This and the following article showcase current Lab work focused on promoting homeland security.



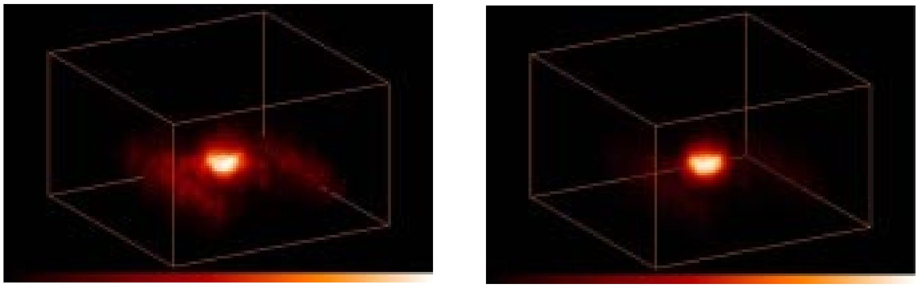
Nuclear (high-*Z*) materials more strongly deflect muons than do the low-*Z* materials found in typical shipping cargoes. In muon scans, detectors above and below a truck would record each muon's path before and after it passes through the cargo. Using this information and muon scattering theory, a computer program would then calculate and display three-dimensional images of objects with high atomic numbers and number densities—signature properties of nuclear materials.

The deflection is also determined by how many nuclei a muon encounters while passing through the material, which is proportional to the number of nuclei per unit volume—the number density. The number density equals the material's density divided by the mass of its nuclei. The materials that most strongly deflect muons have high atomic numbers *and* high number densities. Several low- and high-*Z* materials along with their deflections of cosmic-ray muons are listed in the table.

In muon detection, particle detectors above and below a vehicle or container record each muon's path before and after the muon passes through the cargo. A change in a muon's trajectory means the muon has been scattered by the cargo. Using the path information and muon scattering theory, a computer program then constructs a three-dimensional image of the cargo's dense, high-*Z* objects.

Los Alamos simulations, validated with small-scale experiments (see cover photo), show that cosmic-ray muons can penetrate the 3-millimeter-thick steel walls of a freight truck to detect a block of nuclear or gamma-ray-shielding material 10 centimeters (4 inches) on a side hidden among other cargo, such as livestock or auto parts. The muon scan takes about a minute. People who stay in a vehicle during a scan will receive no more radiation than if they had stayed home in bed. Thus, muon radiography poses no health hazard.

The Los Alamos team can discriminate between different materials even more precisely by measuring muon energies as well as deflections. In computer simulations, this improved technique easily distinguishes between tungsten and steel, for example. Experiments to confirm this discrimination capability are planned for the near future.



Using muon energies, as well as their deflections, produces radiographs that discriminate more precisely between materials. (Left) A muon radiograph based only on deflection data shows an 11-centimeter-diameter tungsten cylinder on a plastic plate with two steel support rails. (Right) A simulated radiograph that includes data on muon energies shows only the tungsten cylinder. This simulation was validated against the experimental image. Combining muon deflection and energy data should enhance the technique's ability to detect both nuclear and shielding materials. (Note: Because of its high number density and atomic number, tungsten is a good nonradioactive surrogate for plutonium and uranium in assessing the capabilities of muon radiography.)

Next Step, Border Inspection?

Border inspectors now use gamma-ray radiography to detect nuclear materials. Because of their high atomic numbers and number densities, nuclear materials strongly absorb gamma rays as well as strongly deflect muons. Thus, nuclear materials are fairly opaque to gamma rays and cast dark shadows in radiographs of vehicles and freight containers.

A gamma-ray scanner uses a radioactive pellet a few millimeters in diameter to produce gamma rays that are energetic and intense enough to scan a large vehicle or container in as little as a few minutes. Although a gamma-ray scan would expose a vehicle's occupants to a negligible dose of radiation—less than a hundredth that of a dental x-ray—occupants are usually removed before scanning, or only the volume of the trailer rig is scanned.

Muon scans will have several advantages over gamma-ray scans. First, the gamma-ray scanner's radioactive pellet must be properly handled and its emissions properly controlled. The pellet must also be replaced after a time about equal to its half-life—the time required for the pellet's radioactivity to decrease to one-half its initial value. Cobalt-60, the most penetrating and hence preferred gamma-ray source, has a half-life of five years. By contrast, cosmic-ray muons do not require radioactive sources that must be replaced. The muons are already there, continuously, wherever the inspection site.

Second, because gamma-ray radiography produces two-dimensional images of the cargo, it can be hard to find a block of nuclear material surrounded by, say, a load of steel auto parts. The superimposed gamma-ray shadows of many objects can prove confusing and create a problem called "clutter." Muon radiography's three-dimensional views overcome this problem.

Third, cosmic-ray muons are also far more penetrating than the gamma rays emitted by even cobalt-60. With

Comparison of Muon Deflections

Material	Atomic Number	Number Density*	Muon Deflection (milliradians)†
Plastic			~2
Aluminum	13	6.0	5
Borosilicate glass	–	–	~4
Iron (steel)	26	8.4	11
Tungsten	74	6.3	27
Lead	82	3.3	20
Uranium	92	4.9	29
Plutonium	94	5.0	30

*Units are 10^{22} nuclei per cubic centimeter.

†The deflection of a 3-billion-electronvolt muon passing through 10 centimeters of various materials with different atomic numbers. For reference, 30 milliradians is about 1.7 degrees.

an energy of 1 million electronvolts, the gamma rays penetrate about 1 centimeter of lead. With an average energy of 3 billion electronvolts (at sea level), muons penetrate nearly 2 meters of lead. Greater penetration depth means the muons can detect nuclear materials surrounded by greater amounts of high-*Z* shielding material or clutter.

Nuclear Threats

Two materials that can be used to make an atomic bomb are plutonium-239 and highly enriched uranium, which contains at least 20 percent of uranium-235. Since both materials have high atomic numbers and number densities, both can be detected by muon or gamma-ray radiography.

Although plutonium-239 can be detected with either neutron detectors or gamma-ray radiography—both techniques are now used for border inspection—uranium-235 presents greater detection problems. It has no significant neutron emission, and its natural gamma-ray emissions can be shielded—usually with a layer of high-*Z* material such as lead or tungsten. In addition, there is much more highly enriched uranium in the world than there is plutonium-239; thus uranium-235 is more available to terrorists (see sidebar).

Although both muon and gamma-ray radiography can detect highly enriched uranium and its gamma-ray-shielding materials, muon radiography's greater penetration depth and more precise materials discrimination promise enhanced detection capabilities. For this reason, work is now underway to utilize the ubiquitous and benign cosmic-ray muons for detecting nuclear contraband. ■

A Terrorist Nuclear Attack

One of the most devastating attacks a terrorist group could mount would be to explode an atomic bomb in a city. If exploded in Manhattan during working hours, for example, a bomb with a yield of only 1 kiloton could kill 200,000 people outright and flatten eleven city blocks.

It is believed unlikely—but not impossible—that terrorists could buy a stolen nuclear weapon on the black market. More likely, they will try to obtain fissile materials to make their own bomb. Al Qaeda operatives have repeatedly tried to buy stolen nuclear materials and recruit nuclear-weapon scientists. The extensive materials on nuclear weapons (including crude bomb designs) found in Al Qaeda camps in Afghanistan underscore the group's interest in such weapons.

Regarding the difficulty of making an atomic bomb, former Los Alamos director Harold Agnew said, "If somebody tells you that making a plutonium implosion weapon is easy, he is wrong. And if somebody tells you that making an improvised nuclear device with highly enriched uranium is difficult, he is even more wrong." Contrary to popular belief, terrorists could make either type of bomb without being killed by radiation exposure as they assembled it.

In theory, as little as 4 kilograms (9 pounds) of plutonium would be needed to make a bomb. As little as 16 to 20 kilograms of highly enriched uranium would be needed to make an efficient bomb; a crude bomb could be made with 50 to 100 kilograms of the uranium. By contrast, the world's supply of highly enriched uranium is estimated to be 1,600,000 kilograms; the supply of plutonium, 450,000 kilograms.

The Researchers

Larry Schultz has a B.S. in agricultural engineering from Oklahoma State University and an M.S. in electrical engineering from Portland State University. He is pursuing a Ph.D. in electrical engineering at Portland State and has been performing research for his Ph.D. at Los Alamos since 2001.

Konstantin Borozdin has an M.S. in nuclear physics from the Moscow Engineering Physics Institute and a Ph.D. in astrophysics from the Moscow Space Research Institute. He came to the Lab as a postdoctoral researcher in 1998 and joined the technical staff in 2001.

John Flower