Graphics and photo illustrations: Fermilab and Sandbox Studio

Solving for X

A proposed new accelerator complex at Fermilab would open up the Intensity Frontier of particle physics.

By Leah Hesla

Depending on your point of view, "Project X" is either an inspired choice—mysterious! intriguing!—for the name of a big science project, a ridiculous title—scary! confusing!—or a placeholder until a better name comes along.

Although "Project X" in fact arose as a temporary designation in a 2007 planning meeting, so far none of the 200-odd suggestions to replace it has stuck. Maybe that's because it's not so easy to capture the essence of the scientific quest at the heart of this proposed new Fermilab accelerator complex.

The $1.8 billion complex would send a beam of protons down a linear accelerator, propel them to either 3 or 8 billion electron volts (GeV), and smash them into a target, creating a gusher of particles: Kaons. Muons. The most intense beam of high-energy neutrinos ever created. And, at the other end of the scale, intense beams of heavy, low-energy nuclei, useful for getting to the bottom of entirely different problems.

These distinctive particle types would be sorted and shipped to different detectors for experiments aimed at answering fundamental questions: How did matter come to dominate the universe? Do electrons and other leptons change into each other, the way the three types of neutrinos do?

An accommodating host, Project X would operate experiments simultaneously so experimenters wouldn't have to queue for beam time. Beam specifications could be custom-tailored for each program—for example, pulsed beams for neutrino experiments and continuous beams for measurements of extremely rare processes. With no downtime other than scheduled maintenance, researchers could collect data continuously. No other accelerator, either existing or on the drawing board, simultaneously serves up so many custom-made beams for particle physics experiments.

In addition, Project X would advance accelerator technologies needed for nuclear energy applications, including transmutation of long-lived radioactive waste into shorter-lived and safer materials.

"There are a lot of exciting and profound questions this facility would tackle," says Young-Kee Kim, Fermilab's deputy director.

What the solutions to those questions have in common can be summed up in one word: Intensity.

X marks the spot

Today's most powerful particle accelerator, the Large Hadron Collider in Europe, operates at what is known as the Energy Frontier: it makes discoveries by slamming particles together at the highest energies possible.

Other experiments work at the Cosmic Frontier, using the cosmos as a particle physics laboratory.

But there is a third approach that complements the other two: the Intensity Frontier. This is where Project X would make its mark.

Intensity refers to the number of particles that accelerator physicists can cram into a beam. More particles mean more collisions with the atoms in a target. The more collisions that take place the more likely it is that an exotic event, incredibly rare but with crucial implications for physics discovery, will show its face.

"If you want to find something very, very rare," says Fermilab physicist Bob Tschirhart, who has spent much of his physics career on the track of the rarest of particle events, "you have to take lots and lots of samples and cleverly avoid subtle fakes."

To illustrate how significant a rare event can be, Tschirhart once showed his wedding photo to a group of local residents. "My marriage was a very rare event for me," he told them, "but it made a big impact on my life."

This leave-no-stone-unturned approach to exploring the nature of the universe complements the higher-profile method of making beams collide at the highest possible energy, says Kim.

"At the Energy Frontier, we hope and expect that scientists will find new particles and new phenomena," she says. "Experiments at the Intensity Frontier will provide insight into these Energy Frontier discoveries or make equally significant independent discoveries," including rare phenomena that may never show up in the highest-energy machines.

The tried, true, and stubbornly accurate Standard Model of particles and forces faithfully renders the family tree of the field's basic constituents, but it doesn't say much about the "out there" physics that preoccupies today's particle physicists: Why do particles come in threes? How did a single fundamental force splinter into four?

Theoretical models abound to address these questions: grand unified theories, string theory, supersymmetry. "These new theoretical models are informed hunches that may herald the existence of new physics," says physicist Doug Bryman at the University of British Columbia and TRIUMF laboratory in Canada. But the theories are only that: models in search of data. By accelerating extremely intense beams of particles, Project X could connect scientists with the "out there" physics phenomena of supposedly forbidden particle decays, neutrino interactions, and ultra-rare processes.

The case for Project X

In 2007, Fermilab Director Pier Oddone asked Kim to convene a steering group to describe a vision for the future of Fermilab as the nation's dedicated lab for particle physics. With Fermilab's Tevatron collider nearing the end of its working life, it was time to outline a new, deliverable US experimental program to meet the needs and goals of the US particle physics community. Over time, the Project X concept took shape. In 2008, the Particle Physics Project Prioritization Panel endorsed developing the concept, and other US laboratories joined the effort.

"We looked at the most exciting physics we wanted to go after and the technical capabilities we had," Kim says. "A lot of effort went into maximizing the science case."

What they came up with was a multi-experiment neutrino research program that would take advantage of Fermilab's existing facilities and use the intense beams from Project X to explore the physics of those maverick particles. Project X would also support the search for rare events using subatomic particles called kaons and muons. It would produce a large number of neutrons and exotic nuclei whose electric dipole moments, should they be discovered, would tell a piece of the tale of how matter came to dominate the world.

As a potentially groundbreaking national project with international collaboration, Project X's accelerator and physics programs are already attracting R&D contributions from all corners, including universities and laboratories in the United States, Canada, India, Italy, Japan, Russia, and the United Kingdom. Four collaborating physics laboratories in India have held their own Project X workshops.

"Project X would establish an Intensity Frontier program in the US that would be world-leading for decades because it provides flexibility to support the long-term evolution of the accelerator complex," says Project X Project Manager Steve Holmes. "It has capabilities beyond what anyone's contemplating today."

Seeking snowballs in hell

Just how rare are the processes that Project X hopes to capture? Consider flavor changing.

Flavor changing refers to a phenomenon in which closely related types of particles can change into each other. The three types of neutrinos are now known to switch flavors. The three types of quarks in an atom's neutrons and protons do the same. So it makes sense to think that the three charged leptons—the familiar electron and its heavier cousins, the muon and tau—can also change into one another. But scientists haven't seen this change yet—with good reason, it turns out. Ordinary laws of physics forbid this transformation in the absence of neutrinos. So for this to happen, out-of-the-ordinary physics would have to get involved.

Even so, scientists suspect that if they looked at enough muon decays, they could catch red-handed a muon morphing into its lightweight sibling with no neutrinos involved.

"We calculated how many muons it would take to spot one that turns into an electron," Tschirhart says. "We'd have to observe 1,000,000,000,000,000,000 muon decays. That's the number of grains of sand on all the beaches in the world."

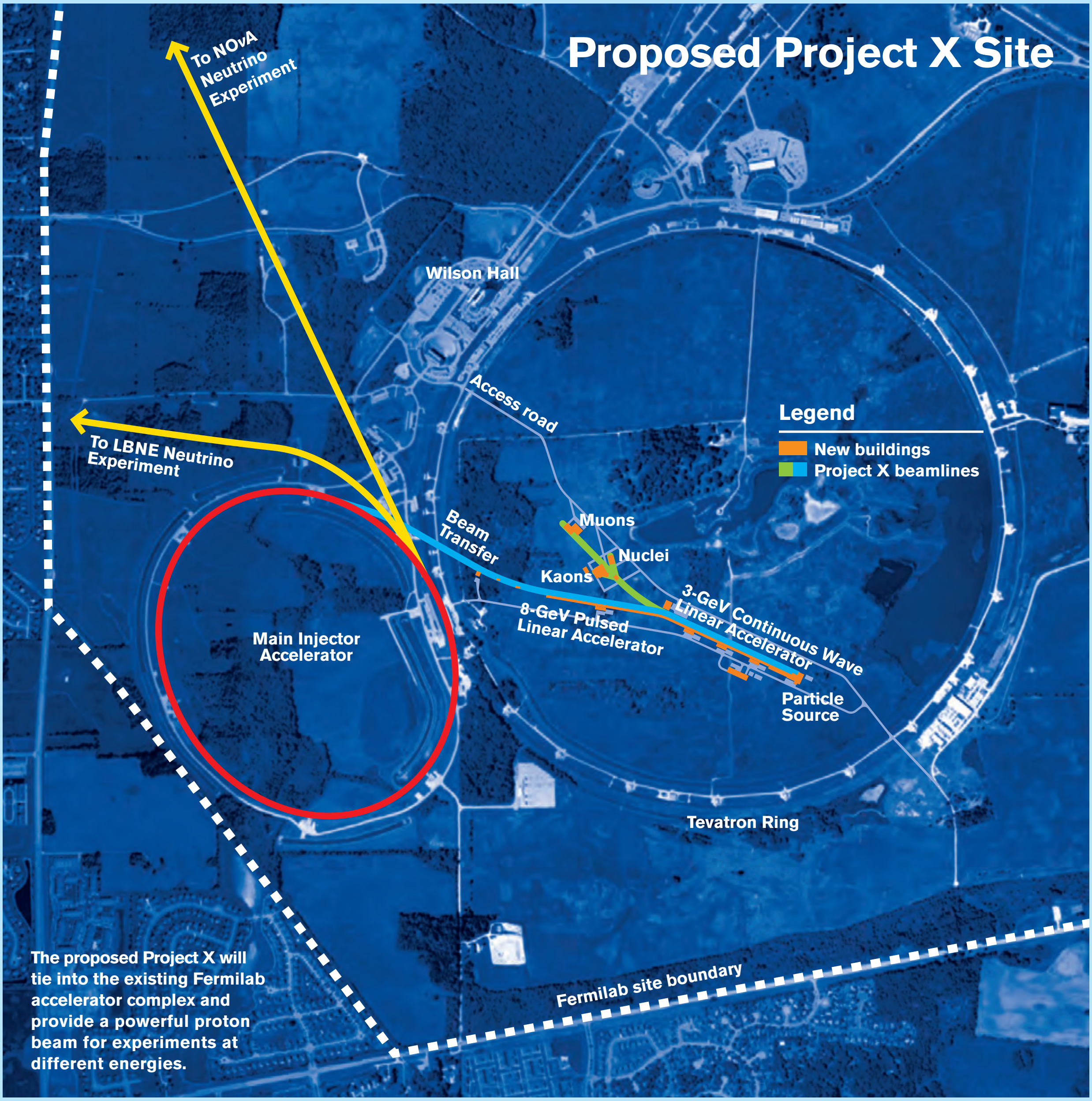
The reason scientists have only a snowball-in-hell's chance of spotting the neutrinoless conversion of a muon to an electron is that the so-called "exchange" particles that mediate the switch are extraordinarily massive. The very existence of these heavy particles violates the law of energy conservation. They arise from the vacuum, from nothingness. Because nature can't long tolerate such outlaws, they pop out of the universe as quickly as they sneak in. Their fleeting existence makes detection almost impossible, and their extraordinary masses require an equally extraordinary energy to push them into the world. And yet, for a split second, they must be very much present.

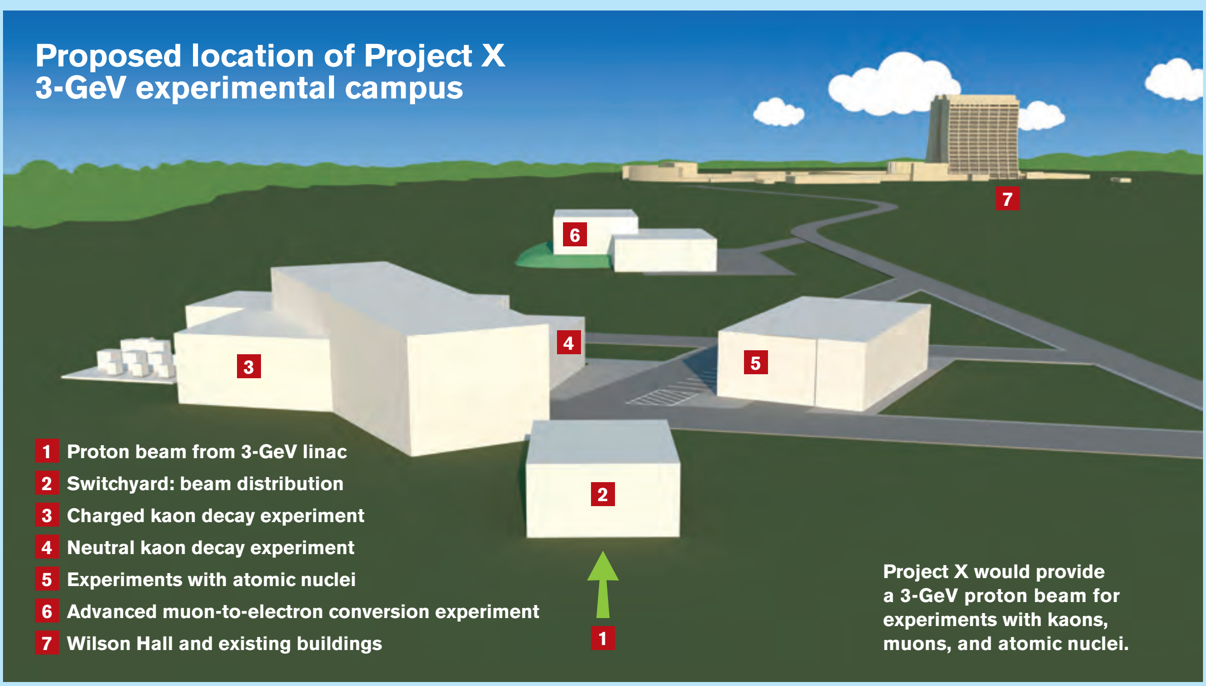
"This business of violating the law of conservation of energy can happen for only tiny, tiny amounts of time," Tschirhart says. "The only chance of catching that outlaw in the act is to take lots and lots of snapshots."

Quarks do it. Neutrinos do it...

Should scientists ever snap a shot of muon-to-electron conversion, the implications for theories that unify all of nature's forces would be huge. A muon changing into an electron in the absence of neutrinos would demonstrate that charged leptons—electrons, muons, and taus—can change flavor. The charged leptons could finally be brought into harmony with neutrinos and quarks, whose flavor-changing ways are well known.

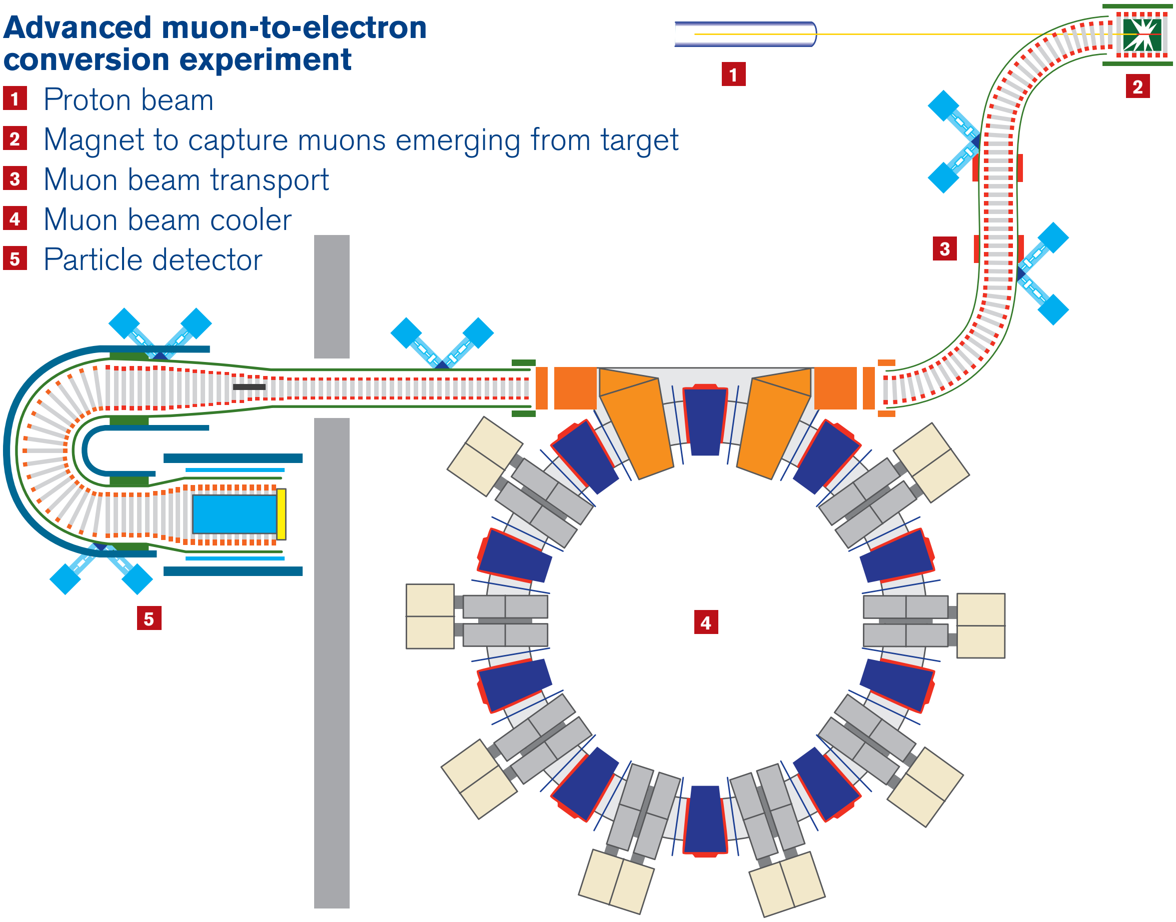
Like the hypothesized muon-to-electron conversion, the decay of a particle called a kaon, containing two quarks, briefly unmasks a fleeting, massive particle that mediates the process. But unlike muon transformations,


Proposed Project X Site
To NOvA Neutrino Experiment
To LBNE Neutrino Experiment
Wilson Hall
Access road
Legend
New buildings
Project X beamlines
Muons
Beam Transfer
Nuclei
Kaons
Main Injector Accelerator
8-GeV Pulsed Linear Accelerator
3-GeV Continuous Wave Linear Accelerator
Particle Source
Tevatron Ring
Fermilab site boundary
The proposed Project X will tie into the existing Fermilab accelerator complex and provide a powerful proton beam for experiments at different energies.


Proposed location of Project X 3-GeV experimental campus
6
7
3
4
5
2
1
1 Proton beam from 3-GeV linac
2 Switchyard: beam distribution
3 Charged kaon decay experiment
4 Neutral kaon decay experiment
5 Experiments with atomic nuclei
6 Advanced muon-to-electron conversion experiment
7 Wilson Hall and existing buildings
Project X would provide a 3-GeV proton beam for experiments with kaons, muons, and atomic nuclei.

Advanced muon-to-electron conversion experiment

1 Proton beam
2 Magnet to capture muons emerging from target
3 Muon beam transport
4 Muon beam cooler
5 Particle detector

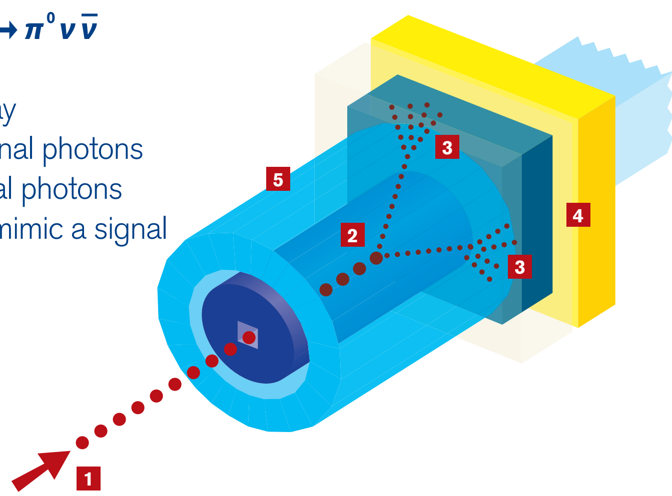


ABOVE: **Quarks transform into each other, and so do neutrinos. Scientists have never observed the charged leptons–electron, muon, and tau–change directly into each other, yet they think these processes should exist. The Project X proton beam (1) could substantially increase the reach of current muon-to-electron conversion experiments by producing and capturing more muons (2, 3) with a narrower momentum range than any other accelerator. State-of-the-art beam cooling techniques (3, 4) would reduce the momentum range of the muon beam by a factor of 10 compared to current experiments. Combined with a high-precision electron detector (5), this "cold," high-flux muon beam would allow scientists to explore the mystery of charged-lepton conversion in greater depth than ever before.**

BELOW: **The proposed Project X accelerator would create enough beam power to pursue the Holy Grail of kaon physics: the observation of the ultra-rare decay of a neutral kaon into a neutral pion and two neutrinos. This process is a unique probe for the matter-antimatter asymmetry in our world and is a strong adjudicator of the existence of physics beyond the Standard Model. The pulsed, pencil-like kaon beam (1) that Project X can produce–a 50-picosecond pulse fired every 40 nanoseconds–is ideally suited for so-called time-of-flight techniques that are needed to determine with high accuracy the momentum of neutral kaons before they decay in the vacuum chamber (2). The design of the photon detector (3, 4) is optimized to precisely measure the energy and direction of the two photons emerging from the decay of the neutral pion and a detector (5) surrounding the vacuum chamber will help identify background processes that can mimic a signal.**

Kaon rare decay experiment: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

1 Kaon beam
2 Vacuum chamber where kaons decay
3 Detector to measure direction of signal photons
4 Detector to measure energy of signal photons
5 Detector to tag processes that can mimic a signal



the sought-after rare kaon decays (about 1 in 10,000,000,000 ordinary decays) are very precisely predicted by the Standard Model, providing a tool to test the theory.

Researchers have observed rare kaon decays at Brookhaven National Laboratory, says Canada's Bryman: "But at Project X we could make a definitive measurement—very accurately—to see if there are any deviations from the Standard Model. Many, many theories that propose extensions of the Standard Model would result in such deviations."

Such measurements could hint at what kinds of creatures these heavy particles are. They could be so-called force carriers, which assist with a particle's transformation from one type to another. They could be supersymmetric particles—the theorized, much heavier partners of particles we know—which to date have never been detected.

If we knew what neutrinos know

While the heavy particles bury their heads in the sand, neutrinos make themselves scarce by zipping through space—and us—with scarcely an interaction at all. In the same moment neutrinos are made in the laboratory, they fly away at light speed. Containing them is like trying to hold water in a butterfly net.

They're worth the chase, though.

"This has been a problem in accelerator-based neutrino physics since it was started in the early sixties. You never have enough events," says Stanford University neutrino physicist Stanley Wojcicki. Now five decades into using large particle accelerators and detectors for neutrino-watching, scientists hope that, with greater multitudes of neutrinos, many more events will present themselves.

"In these neutrino areas of research, we're still infants," Kim says. "There's so much to learn."

Current portraits of neutrinos are painted in broad strokes, generating more questions than answers. How frequently do the three flavors of neutrinos change from one to another? Some flavors dominate more than others; how much more? The difficulty with neutrinos is that the masses of the three types differ by a hair's breadth. It makes measurements tough and sorting them a chore.

"Recently we've observed possible anomalies in neutrino experiments, and it's motivated us to pursue even more detailed studies," Wojcicki says.

Scientists track neutrinos over long distances or examine vast numbers of them to get a quantitative bead on their flavor-changing game. If they can pin down values for all three oscillations, it will go a long way toward finally determining the tiny masses of the three neutrino types. Ultimately, scientists hope to understand what role neutrinos played in the evolution of the universe.

Free of charge? Really?

Experiments at Project X would also look at the matter-antimatter difference in another light.

"One of the embarrassing aspects of the Standard Model is that it doesn't draw a significant distinction between matter and antimatter, which by itself would be fine, but we're in a world full of matter," Tschirhart says.

One strategy for saving face is to seek out hidden electric dipole moments, or EDMs, a fancy term for a spatial separation between positive and negative electric charges. If scientists should find them concealed inside atoms, it would indicate a violation of the principle of physics that places matter and antimatter on equal footing.

Electric dipole moments are everywhere in nature. Some EDMs are more obvious than others, and plenty of particles, such as neutrons, appear to have no EDM at all, which would mean that their constituent negative and positive charges effectively sit on top of each other.

The math says it's possible that what may look like perfectly overlapping equal and opposite charges inside an atom could actually be an absurdly small dipole moment. In these as yet undiscovered EDMs, a mere 10^{-26} centimeter separates an electron's worth of charge from its opposite. Its size is to a neutron what a hair's breadth is to the Earth.

Such tiny EDMs would be easy to miss, so scientists have proposed inspecting scads of ostensibly EDM-free samples for some minuscule dipole moment taking refuge inside the atom. At Project X, the search would expose beams of neutrons and heavier neutral isotopes such as francium and radon to an electric field. If the atoms, previously believed to lack charge, are indeed harboring EDMs, they'll perform a little twist, lining up with the electric field like a compass needle pointing north.

"Project X would provide a fantastic beam that would be a whole new ballgame in terms of isotope yield," says Argonne National Laboratory's Jerry Nolen, an expert in crafting just the right beam for such experiments. "It can produce previously unheard of quantities of these isotopes," about a thousand times more than current machines. With higher statistics come more opportunities for locating telltale signs of matter-antimatter asymmetry.

If discoveries continue this way—breaking conservation laws, reuniting family members, assigning ever-more-precise numbers—physicists may be able to recreate the natural matter-antimatter symmetry that they believe lies at the root of the particle genealogy of the universe.

Charting a course to the Intensity Frontier

The Project X scheme, developed over a couple of years and first presented in 2010, gives researchers a multi-year framework for R&D aimed at delivering a machine that ably supports the experimental goals. This means developing a reliable method for generating a continuous, high-intensity proton beam; pushing the limits of superconducting radio-frequency technology, which is used to accelerate the particles in the beam; and perfecting the design of instruments for routing particles to the different experiments.

"We want to make sure we're ready to go whenever the word comes down from on high," Holmes says.

Collaborators hope to begin the five-year construction project in 2016. With steady progress, by 2020 the US could have a remarkable tool for unearthing extraordinary phenomena at the Intensity Frontier.

The small matter of coming up with a permanent name for the proposed new accelerator has no one worried. "If the name were holding us back, we'd choose something different this afternoon," Holmes says. "Project X is a bit of a brand name at this point. If we ever choose a new name, there should be an X in it."