Project X and the Science of the Intensity Frontier

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The recent P5 subpanel of the High Energy Physics Advisory Panel identified three frontiers of scientific opportunity for the field of particle physics: the energy frontier, the intensity frontier and the cosmic frontier. Project X, a proposed new high-intensity proton source at Fermilab, has the potential to be the flagship of discovery at the intensity frontier. Project X would deliver very high-power proton beams at energies ranging from about 2.5 to 120 GeV. It would also offer unprecedented flexibility in the timing structure of beams (pulsed or continuous wave, varying gaps between pulses, fast or slow spill) and in the variety of simultaneously delivered secondary beams. These features would make Project X the foundation both for fundamentally new experiments and for significant advances in ongoing experimental programs in neutrino physics and the physics of ultra-rare processes.

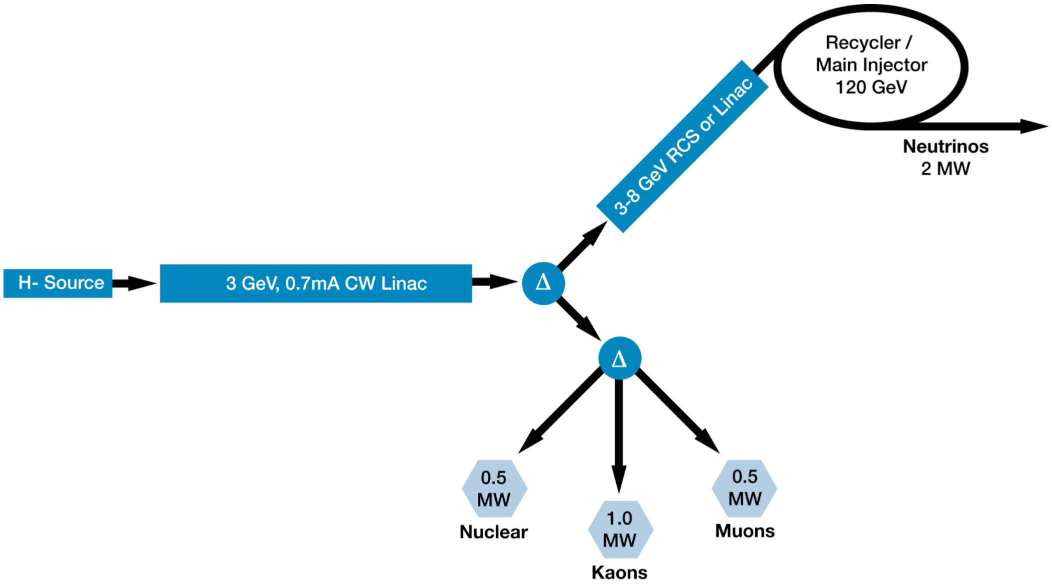
Physics at the intensity frontier is closely linked with both the energy and the cosmic frontiers. Answers to the most challenging questions about the fundamental physics of the universe will come from combining what we learn from the most powerful and insightful observations at each of the three frontiers. Addressing most of the questions under investigation at the energy and cosmic frontiers also requires measurements at the intensity frontier.

Understanding the neutrinos and their masses, for example, addresses the central question of the ultimate unification of forces. Matter-antimatter asymmetry in the behavior of neutrinos might elucidate one of the deepest mysteries of physics: Why do we live in a universe made only of matter, with no antimatter? Results from experiments now underway around the world will shape the future course of neutrino research. No matter what they find, Project X, with the world's most intense neutrino beams, will be key to the next steps in neutrino physics.

Characterizing the properties and interactions of new particles that will likely emerge from discoveries at the Large Hadron Collider will require the perspective of experiments at the intensity frontier. If experiments at the LHC discover supersymmetry, for example, intensity-frontier searches have the potential to make critical distinctions among different models of this phenomenon. And if LHC experiments should fail to see new physics, the intensity frontier would be the only approach to Terascale physics.

High-intensity particle beams spur experimental investigations wherever dramatic advances require extraordinary precision and clean, background-free experimental conditions. They provide the capability for neutrino investigations, such as long-baseline experiments, that require detailed, precise studies of energy spectra in order to detect matter-antimatter asymmetry in neutrinos. They allow physicists to focus sharply on barely observable processes with great scientific significance, such as the high-priority search for the conversion of muons to electrons. In experiments now limited by statistics, such as the search for the transition of a quark of one flavor to an identically charged quark of a different flavor, they make possible the precise measurements that are essential for discovery. They provide the exacting experimental conditions required by extremely challenging experiments, such as the search for rare decays of kaons, a window to phenomena at ultrahigh energies well beyond the LHC's reach. Finally, they make possible experiments that may be crucial for a true understanding of physical phenomena such as electric dipole moments of atoms, potentially an incisive probe of matter-antimatter asymmetry at energy scales beyond the Standard Model.

Project X opens the window on a whole spectrum of new experiments at the intensity frontier. The subsequent discussion divides the scientific opportunities provided by Project X into four areas: neutrinos, muons, kaons, and fundamental physics using nuclear physics techniques. With the power of Project X, they all attain new, hitherto unattainable, capabilities for discovery. Project X would also represent a first step toward potential future particle physics facilities, such as a neutrino factory or an energy-frontier muon collider.



Project X, a high-power proton facility, would support world-leading programs in long-baseline neutrino physics and the physics of rare processes. It would be unique among accelerator facilities worldwide in its flexibility to support multiple physics programs at the intensity frontier. Project X is based on a 3 GeV continuous-wave superconducting H- linac. Further acceleration to 8 GeV, injected into Fermilab's existing Recycler/Main Injector complex, would support long-baseline neutrino experiments. Project X would provide 2.0-2.1 MW of total beam power to the 3 GeV program, simultaneously with 2 MW to a neutrino production target at 60-120 GeV. A multilaboratory collaboration with international participation has undertaken the development of Project X.

Neutrino Physics

Neutrino oscillation is the first laboratory-observed phenomenon in particle physics that the very successful Standard Model cannot explain. It demonstrates that neutrinos have mass and that lepton flavor is not conserved, and it points to new physics at a very high energy scale beyond the scope of the Standard Model. Since the pioneering experiments that first definitively observed neutrino oscillation, many other investigations have contributed to a better understanding of the oscillation phenomenon and to a quantitative knowledge of the parameters describing it. The discovery of neutrino mass has opened a new world to explore.

The initial results, besides revolutionizing our understanding of neutrino physics, have pointed the way toward new scientific opportunities. Project X is an accelerator complex conceived and designed with the goal of exploring these opportunities to the full by taking maximum advantage of the existing Fermilab infrastructure. Adding a new high-power neutrino beam aimed at a new underground detector complex would create a world-leading facility to probe the mysteries of neutrino physics. The May 2008 report of the P5 HEPAP subpanel identifies eight compelling issues in the neutrino field; Project X would address five of them; large detectors in a deep underground laboratory would address an additional one.

Project X and the key questions in neutrino physics

The oscillation phenomenon can be described by six independent parameters: two mass-squared differences, three mixing angles, and a CP-violating phase. The mass-squared differences are already known at the level of a few percent. Two of the angles, θ_{12} and θ_{23}, are known at the level of a few degrees. The third angle, θ_{13}, however, has been shown only to be comparatively small, the current limit being about 10 degrees. At present there are no reliable theoretical constructs that would either explain the values of the known parameters or predict what should be the value of θ_{13}.

Measurement of θ_{13} is an essential first step towards mapping the strategy for optimal pursuit of the two most important questions: What is the mass hierarchy of the three neutrinos? Is there matter-antimatter asymmetry (CP violation) in the neutrino sector? The mass hierarchy would yield very important information concerning the origin of neutrino mass. Observation of CP violation would be evidence that neutrinos in the early universe played the central role in creating the cosmic predominance of matter over antimatter. Several experimental efforts around the world are embarked on the effort to measure θ_{13}. Recent results have very tentatively suggested that this angle may be large enough to be within reach of near-term experiments (MINOS; the three reactor experiments: DoubleChooz, Daya Bay and RENO; and the next generation long baseline experiments T2K and NOvA). If these indications hold up, detailed planning for a Project X neutrino program could proceed with the knowledge of the value of θ_{13}.

The US program in this area is based on a Project X neutrino beam directed toward large detectors in the proposed Deep Underground Science and Engineering Laboratory. The primary measurement of the Project X long-baseline neutrino experiment is determination of the energy dependence for the $\nu_\mu \rightarrow \nu_e$ transition. The mass hierarchy sensitivity increases with the length of the neutrino flight path through matter. The 1300-km distance between Fermilab and the Homestake Mine in South Dakota, site of the proposed DUSEL, is a good compromise between the neutrino event rate, which decreases as the square of the distance, and sensitivity to the mass hierarchy. There is currently an active R&D effort on the optimum detector system for this program. The two technologies that look most promising are water and liquid argon. Water Cherenkov technology is more highly developed at this time, but per unit mass it provides less sensitivity than liquid argon. Physicists recognize that probing the issue of CP violation requires very large detectors, even with the intense Project X beam. Thus, for example, they calculate that it would take about 300 kt of water or 50kt of liquid argon to achieve the required precision, very likely deployed in several smaller (about 100kt for water) modules. The currently planned depth for the detectors is 4850 feet.

If the value of θ_{13} is large enough ($\sin^2 2\theta_{13} > 0.01$), the new planned long-baseline experiment would be able to determine conclusively the neutrino mass hierarchy (if NOvA has not already determined it), and would be sensitive to a large fraction of potential values of the CP violation phase. The requirements for the observation of CP violation are quite insensitive to the value of θ_{13} as long as $\sin^2 2\theta_{13} > 0.01$, and these requirements cannot be satisfied without access to the beam intensities provided by Project X, and to large-mass detectors such as those contemplated for the proposed DUSEL.
There is a tantalizing pattern in the measured neutrino mixing angles: $\sin^2\theta_{23} \sim 1/2$, $\sin^2\theta_{12} \sim 1/3$, and $\sin^2\theta_{13}$ small. This pattern may be due to a hitherto hidden symmetry that leads to special values of the mixing angles. The Project X neutrino program is well suited to investigate the possibility of a new symmetry through its capability to measure both θ_{13} and θ_{23} with high precision and sensitivity.

Short-baseline physics

The Project X neutrino beamline aimed at the proposed DUSEL would provide a neutrino beam of unprecedented intensity—the most intense neutrino beam in the world. Many new precision high-statistics neutrino experiments would now become possible with detectors relatively close (~1 km) to the target at Fermilab. Thus, in addition to making possible the incisive study of neutrino oscillation, the Project X facility would also provide opportunities for new experiments with specialized detectors designed for specific experiments. The recent workshop at Fermilab did not addressed this topic, but examples of such studies from previous work include neutrino elastic scattering (information on $\sin^2\theta_W$ and neutrino anomalous magnetic moment), measurement of total and partial cross sections, and the search for other weakly interacting particles. In addition, new beams from Project X's high-intensity 2-3 GeV source could be constructed for other investigations, for example for the study of the LSND anomaly with significantly higher precision than is possible with the MiniBooNE experiment.

Nonstandard neutrino physics investigations

Precision neutrino experiments based on Project X provide the opportunity to search for the footprints of new physics in the neutrino sector. Possible theoretical scenarios include nonunitarity in the lepton mixing matrix (induced, for example, by mixing of active and sterile neutrinos), non-standard interactions of neutrinos with other particles, and more exotic scenarios like CPT and Lorentz violation. Some of these effects are most easily studied in near detectors, while others require a far detector. In general, high statistics, a broad energy spectrum, and low backgrounds are essential to search for new physics in neutrino experiments. The contemplated Project X-to-DUSEL program meets these requirements. Simulations show it has the potential to improve current bounds on some nonstandard effects in the neutrino sector by up to one order of magnitude. In some very special models, discovery of new physics might be possible.

Besides the neutrino experiments, the proposed experimental setups can also be used to search for long-lived, weakly interacting hidden sector particles produced in the target as predicted in some recent dark matter models.

Long-term vision for neutrino physics

The global neutrino physics community generally agrees that the neutrino program must be planned in stages, with the results of successive stages shaping the stages that follow. It is convenient to talk about three stages:

a) Currently approved experiments, focused on determining θ_{13}. This stage should produce important results (or limits) on a time scale of two to five years.

b) Super Beam stage, of which the Project-X-related effort would be the US contribution. There are efforts along related lines in both Asia and Western Europe. First results might be forthcoming here in about 10 years.

c) New-facility efforts, oriented around a neutrino factory or a beta beam facility. The determination of the need and feasibility of such facilities must await results from the preceding stages.

The intense proton source of Project X would be a crucial resource *regardless of the value of* θ_{13}, and regardless of whether the first two stages above suffice for our study of neutrino physics, or whether it proves essential to build a neutrino factory. The latter facility would require an intense proton source like that proposed for Project X. Thus, should physics point towards construction of such a facility, the US neutrino program would already have made the first step towards it with Project X.

Neutrino programs abroad

The scientific communities of other regions have also recognized the importance of neutrino physics. Both Western Europe and Asia have ongoing experiments and long-range plans for pursuing scientific opportunities in neutrino physics.

In Japan, several super beam options extending beyond the ongoing T2K project are under consideration. Currently the main possibilities are:

a) A 100 kt liquid argon detector in Okinoshima, a small island 658 km away from the neutrino source. The beam would be slightly off-axis. The same detector would study both the first and second oscillation maxima.

b) 540 kt water Cerenkov detector at Kamioka, 295 km away. A run with neutrinos and a much longer run with antineutrinos would cover only the first oscillation maximum.

c) Two 270 kt water Cerenkov detectors, one at Kamioka and the other in Korea, about 1000 km away. The two detectors would cover the two maxima separately, one in each detector. This scenario contemplates roughly equal runs with neutrinos and antineutrinos.

The Western European scientific community is actively discussing the development of a European strategy for neutrino physics, with involvement of the CERN Council and the CERN Scientific Policy Committee. A neutrino subpanel of the CERN Scientific Policy Committee has formed with a mandate to review the state of the field and to produce a report in December 2009. Three options for large infrastructure for neutrinos are under consideration: a second-generation super-beam; a beta-beam facility; and a neutrino factory. Each option poses significant technical challenges in the accelerator facility and the neutrino detectors.

An energetic European R&D program is in place, funded through the European Commission Framework Programmes. There appears to be a growing realization in Europe that establishing the far-reaching program needed to discover leptonic CP violation and to unravel the physics of flavor will require an international approach.

Kaon Physics

The existence of flavor for quarks and leptons gives the Standard Model its structure of families and generations of elementary particles. This family structure explained the absence of expected effects among kaons in a way that led to the prediction of the charm quark. Kaon decays also led to the observation of matter anti-matter asymmetries (CP violation), and to the Cabibbo-Kobayashi-Maskawa model, which in turn predicted the existence of a third generation of particles. Mixing of neutral B mesons, in a role like that played by neutral kaon mixing in establishing the mass range for the charm quark, was the first experimental observation that correctly anticipated the large value of the top quark mass. The dramatic discovery of neutrino masses provided the first incontrovertible evidence that the Standard Model is incomplete, and may provide a window to the unification of forces. Several of the great questions of particle physics have flavor at their core, and flavor physics can play a unique and crucial role in the progress of the field.

The flavor of new physics at the Intensity Frontier

Several elements directly associate LHC physics with flavor. Without a Higgs or some other mechanism of electroweak symmetry breaking (EWSB), quark flavor effects would not even exist. All flavor phenomena in the Standard Model are encoded by a handful of input parameters that currently lack explanation. But beyond the Standard Model, flavor phenomena can cover a much wider landscape and are even more strongly entangled with the dynamics of symmetry breaking. New particles, such as charged Higgs particles or supersymmetric partners, can mediate flavor-changing processes. New flavors may appear, either in the form of new generations, or as exotic partners of standard quarks (such as composite quark states in "little Higgs" models). New sources of CP violation can arise from couplings of non-minimal Higgs sectors or of superpartners. All of these new sources of flavor effects put the natural suppression of most flavor-violating phenomena in the Standard Model in jeopardy, and physicists expect much larger effects from new Terascale physics at the LHC. In the context of Beyond Standard Model (BSM) theories, this is a fundamental issue called "the flavor problem."

Equally important is that in several BSM frameworks, the parameters of flavor are not just arbitrary inputs but instead are the result of dynamics or symmetries of the underlying theory. Unified theories predict relations between the couplings of quarks and leptons. In supersymmetric models with neutrino masses, a mix of symmetry relations and dynamics connects neutrino mixing and flavor transitions in the charged-lepton sector. In extradimensional theories, the family replicas can be understood as different branes on which fermions are bound to live, and mixings are tied to the relative positions of these branes in the extra dimensions. In super-symmetric theories, the large value of the top quark mass can dynamically generate electroweak symmetry breaking, making EWSB, in some sense, a flavor-driven phenomenon. Finally, the numerical coincidence of the top mass value with the scale of EWSB is yet another mysterious hint of a possible direct connection between EWSB and flavor.

These connections between symmetry breaking and flavor, as well as the flavor mysteries of neutrino masses and the matter-antimatter asymmetry of the universe, strongly suggest that flavor will play a key role in exploring the new physics landscapes unveiled by the LHC. Most conceivable new physics manifestations will provide new sources of flavor phenomena, underscoring our need to address the flavor problem. The optimal approach to understanding flavor will depend on the details of the discoveries. It is sensible to expect, on the basis of the history of particle physics and of the explicit models of new physics available today, that experiments at the Energy Frontier and flavor experiments at the Intensity Frontier will provide complementary advances in the coming phases of exploration of the laws of nature.

Kaon physics opportunities at the Intensity Frontier

Advanced rare-decay kaon experiments have probed branching fractions in the 10^{-11} – 10^{-12} range including the rarest particle decay ever observed, $B(K_L \rightarrow e^+e^-) = 9x10^{-12}$, and the discovery of the sought after process $B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 16x10^{-11}$. These measurements were achieved with 20-50 kW of "slow extracted" proton beam power from proton synchrotrons. Next-generation experiments, aimed at 1000-event Standard Model sensitivity to the $K \rightarrow \pi\nu\bar{\nu}$ process, require branching fraction sensitivities at the 10^{-14} level, which require beam power in excess of 200 kW per experiment with high-duty-factor beams. High-duty-factor beams have historically been generated with slow-extracted-beam techniques, which do not scale well to the required high power of these next generation experiments. Continuous-wave-linac technology presents an opportunity to break through this power barrier and provide high-power, high-duty-factor proton beams to drive next-generation experiments.

- **Precision measurement of** $B(K_L \rightarrow \pi^0 \nu\bar{\nu})$ New physics can induce substantial enhancements to the branching fraction $B(K_L \rightarrow \pi^0 \nu\bar{\nu})$. The Standard Model process $K_L \rightarrow \pi^0 \nu\bar{\nu}$ can be calculated with precision and is uniquely sensitive to matter-antimatter asymmetries of physics beyond the Standard Model. Measuring this highly suppressed process, predicted to be only 30 parts per trillion in the Standard Model, requires very intense kaon sources. The JPARC facility in Japan is pursuing discovery of this process with an eventual sensitivity of a single event at the Standard Model level. The beam power available with Project X allows consideration of experiments with much higher sensitivity, at the 1000-event level in the Standard Model. Pursuit of this challenging measurement is complicated by the fact that all particles in both the initial and final states are neutral and consequently hard to detect. The high-precision timing properties of proton linac technology provide experimental tools (time-of-flight techniques) to strengthen the experimental signature and reject background processes to the required level.

- **Precision measurement of** $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ New physics can likewise induce substantial enhancements to the charged mode $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ rate in the Standard Model, which can be calculated precisely. Measuring this highly suppressed process, 80 parts per trillion in the Standard Model, with precision requires very bright kaon sources and consequently extremely intense proton drive beams. This process was discovered at Brookhaven's proton facility, the AGS, using "stopped kaon" techniques fueled with a high-intensity, low-energy K^+ beam. Today in Europe CERN is pursuing a next step in sensitivity beyond discovery with a promising new technique driven by the SPS proton facility. The proven techniques developed at the Brookhaven AGS can be further exploited to reach 1000-event sensitivity using the Fermilab Tevatron in a "stretcher" configuration driving a Stage-I experiment (10 times the AGS) and ultimately with Project X, which could deliver 200 times the rate of K^+ decays realized at the AGS.

- **Precision measurement of interference phenomena in the neutral kaon system** The neutral kaon system is a very sensitive interferometer by virtue of the tiny relative mass difference (1 part in 10^{15}) between the K_S and K_L physical mass states. Measurements in the neutral kaon system today (CPT violation studies) are among the most sensitive probes of the microscopic structure of space-time. The proton beam power available at Project X would drive next-generation experiments to probe inverse mass differences between K^0 and anti-K^0 approaching the Planck scale where the very structure of space-time may become discontinuous. The continuous wave proton linac of Project X can be further exploited to produce a very intense pure K^0 source with negligible anti-K^0 contamination by virtue of the linac energy operating point set above the K^0 production threshold but below the anti-K^0 threshold. This K^0 source can drive experiments uniquely sensitive to matter-antimatter asymmetry in quark interactions and decays.

Muon Physics

Of all known fundamental particles, the muon is the most massive that can be manipulated and studied in detail in the laboratory. The muon owes this property to its longevity; a muon at rest lives longer than two microseconds – a long time where particle physics experiments are concerned. All other fundamental particles heavier than the electron either manifest themselves only as composite objects (the light quarks, for example, are always found inside hadrons like the proton and the pion) or are too short lived, like the tau lepton, which lives for a few picoseconds at rest.

The muons' relatively light mass and long lifetime allow physicists to produce them in large quantities for precision experiments addressing fundamental physics questions. Muon experiments come in two categories: high-precision measurements of muon properties and searches for very rare muon processes. The unprecedented proton beam intensities from Project X, combined with Fermilab's flexible accelerator complex, would allow access to tailor-made, incredibly intense muon beams that might reveal undiscovered properties of the fundamental physical world.

Precision measurements

Because the muon is a fundamental particle, physicists can compute its properties within the Standard Model of particle physics with great precision. Actually measuring these properties with similar precision would thus convey sensitivity to very small deviations of the current understanding of nature at the Terascale and beyond.

- **The muon magnetic moment**
  The strength of the interaction of muons with magnetic fields is known to 0.54 parts per million. However, theorists can estimate the theoretical value for this quantity at the level of 0.42 parts per million. Curiously, the best theoretical estimates and the best measurements of the muon magnetic moment differ at around the 3.2 σ level, $\Delta a_\mu = (255 \pm 80) \times 10^{-11}$ where $a_\mu = (g-2)/2$ is the anomalous magnetic moment of the muon and g is its gyromagnetic ratio. This difference has invited speculation within the theoretical particle physics community and has motivated experimenters to pursue next-generation experiments that would improve on the experimental measurement of $a_\mu = (g-2)/2$ by a factor of two. A concrete proposal for such an experiment is currently under discussion at Fermilab. On the same time scale, the precision of the Standard Model estimate of $a_\mu = (g-2)/2$ is also likely to improve by about a factor of two. Hence, if the current $a_\mu = (g-2)/2$ discrepancy is a consequence of physics beyond the Standard Model, the next-generation experiments should observe a discrepancy of at least five or six sigma. Regardless, physicists expect that information from the muon anomalous magnetic moment and data from new physics searches at the LHC will complement each other to provide a sharper picture of physics at the Terascale.

The Project X era should bring even further improvements in the measured uncertainty of a_μ =(g-2)/2. Indeed, the limiting factor in our ability to verify whether there is a discrepancy with the theoretical prediction is likely to be the ability to compute a_μ =(g-2)/2 in the context of the Standard Model. Novel theoretical methods must be developed for
the subsequent generation of measurements of the muon magnetic moment in order to significantly advance the understanding of particle physics.

- **The muon electric-dipole moment**
  A permanent electric dipole moment for fundamental Standard Model fermions requires violation of the discrete symmetry CP. This is the case in the Standard Model, albeit in a very suppressed way. The Standard Model with zero neutrino masses predicts the electric dipole moment of the muon to be $d_\mu \sim 10^{-35}$ e-cm. Extensions of the Standard Model that accommodate massive neutrinos often predict much larger d_μ values. Furthermore, independent of the physics responsible for neutrino masses, virtually all models of new physics at the TeV scale predict $d\mu$ values much larger than the Standard Model estimate. Indeed, high-precision measurements of d_μ will ultimately be sensitive to new physics at energy scales above several tens of TeV, as long as the new physics violates CP invariance strongly.

  The current experimental bound on the muon electric-dipole moment is $d_\mu < 1.8 \times 10^{-19}$ e-cm. Physicists expect next-generation experiments, including one closely associated to the current proposal to measure a_μ at Fermilab, to be sensitive to $d_\mu \sim 10^{-(20\text{-}22)}$ e-cm. This level of sensitivity should allow experimenters to probe several well-motivated models of physics beyond the Standard Model. Project X would enable experimental set-ups sensitive to $d_\mu \sim 10^{-24.}$ Depending on the physics revealed by the LHC, such a sensitive measurement of, or upper bound on, d_μ (assuming it is not discovered by the previous round of experiments) will either reveal a lot about the CP-properties of the new Terascale physics, or allow physicists to probe for physics beyond the reach of the high-energy machines.

Rare processes

Physicists have never observed processes in which a muon changes into a different charged lepton--an electron for example. Until the end of the twentieth century, scientists saw this as a consequence of a fundamental physics principle: the conservation of individual lepton flavor charge: for any physics process, the number of leptons of a given flavor is absolutely conserved.

Now, however, experiments have definitively observed the violation of individual lepton flavor charges. The phenomenon of neutrino oscillations allows the detection of a muon neutrino produced, say, via pion decay, as an electron neutrino. Furthermore, neutrino experiments have shown that for charged-current processes (processes where a charged-lepton is produced/destroyed while a neutrino is destroyed/produced), the violation of individual lepton flavor charges is very large (that is, the lepton mixing angles are large). Flavor violation went undetected for so long because observing the lepton-flavor number violation requires sensitivity to the difference in neutrino masses, an observation that required neutrino experiments with very long baselines.

Since lepton flavor charges are not conserved, it must be possible to observe the phenomenon of charged lepton flavor violation. However, the expected order of magnitude of the different rates is unknown, because the rate for different CLFV processes depends dramatically on the physics that gives mass to neutrinos. Since physicists are still in the process of trying to understand where neutrino masses come from, no unambiguous expectation yet exists for the rate of the different CLFV processes, beyond the generic expectation that all of them are non-zero. One known contribution comes directly from the neutrinos. It applies to scenarios where the neutrinos are Dirac fermions and hence obtain their masses through the Higgs mechanism, like the electron or the quarks. For example, in this scenario, the branching ratio for a muon to decay into an electron and a photon is predicted to be absurdly small, $Br(\mu \to e\gamma) \leq 10^{-54}$.

Other simple, well-motivated extensions of the Standard Model that explain the origin of neutrino masses predict CLFV rates many orders of magnitude larger than the naive neutrino contribution. Such models are often able to saturate the current experimental upper bounds. In a nutshell, since the source of neutrino masses remains unknown, no Standard Model expectation for CLFV rates exists. The converse also applies: measuring the rates for different CLFV processes will yield important insight into the origin of neutrino masses.

More generally, the fact that the conservation of individual lepton flavors is not a law of nature implies that the existence of new heavy particles and new forces can lead to large rates for CLFV. Indeed, all models of physics beyond the Standard Model predict CLFV rates that are usually quite high, especially if the new particles have masses below the 1-TeV scale. Theorists have made detailed computations in all well-known new physics paradigms, including supersymmetry, extra space dimensions (large and flat, or small and warped), and technicolor-like mechanisms. Universally, they point to CLFV rates within one to several orders of magnitude beyond current experimental bounds.

Among all CLFV searches, those involving initial-state muons are the most mature and provide by the far the best constraints. This is a consequence of the muon's light mass and long lifetime. A discussion of three of these processes follows. (There are also other promising searches, including those for muonium-antimuonium oscillations and other searches for lepton number violation with initial-state muons.)

Searches for muon-number-violating processes appear to be the most promising way to explore experiments with low-energy, intense muon beams in the Project-X era. Potential next-generation versions of many of these experiments are sensitive to new physics at several tens to several hundreds of TeV. New particles may exist beyond the 1 to 10 TeV scale, that are unobservable at the LHC but that may leave an imprint in CLFV.

- $\mu \to e\gamma$ decay: Searches for $\mu \to e\gamma$ usually involve stopping large quantities of μ^+ muons in a thin target and looking for back-to-back positron-photon pairs with a well defined energy, $E_\gamma = E_e = m_\mu/2$. To improve on the current experimental upper bound $Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$, on top of intense muon fluxes, requires a high-granularity calorimeter capable of precisely measuring the photon energy in order to fend off the unavoidable physics background from $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$ decays. Experimenters must also minimize the likelihood that two muons decay at the same time and place, one yielding an electron and the other a photon with the right energy tag. The best way to do this is to minimize the instantaneous muon flux via continuous muon beams. The MEG experiment, currently taking data at PSI, aims at being sensitive to $Br(\mu \to e\gamma) \leq 10^{-13}$. A potential upgrade of MEG may reach sensitivities as low as 10^{-14}.

  With Project X, experimenters could use a continuous-wave beam to look for $\mu \to e\gamma$, or to improve the understanding of this rare process if it is observed in next-generation experiments (in which case, it may also be useful to study the $\mu \to e\gamma$ decay of polarized muon beams). However, sensitivity beyond 10^{-15} appears beyond the reach of *next*-next-generation experiments unless innovative ideas regarding the detectors emerge.

- $\mu^+ \to e^+ e^+ e^-$ decay: Searches for $\mu^+ \to e^+ e^+ e^-$ also involved stopping large μ^+ samples on thin targets and fully reconstructing the three-electron final state. The experimental challenges are not unlike those for $\mu \to e\gamma$, with some advantages. The irreducible physics background $\mu^+ \to e^+ e^+ e^- \nu_e \bar{\nu}_\mu$ is not as dangerous here, while the presence of three electrons in the final state allows reconstruction of the decay vertex and more effectively eliminates background from coincident muon decays. Like searches for $\mu \to e\gamma$, searches for $\mu^+ \to e^+ e^+ e^-$ also need continuous beams. The current experimental bound is $Br(\mu \to eee) < 1.0 \times 10^{-12}$. Currently, no proposals exist to improve our sensitivity to this rare muon process.

  Project X would allow improving on the sensitivity to $\mu^+ \to e^+ e^+ e^-$ decays by at least three or four orders of magnitude, assuming a significant effort to develop new high-rate detector technologies. As with searches for $\mu - e$ conversion in nuclei, described below, physicists predict that searches for $\mu \to eee$ are sensitive to a broader range of new physics than searches for $\mu \to e\gamma$.

- $\mu - e$ conversion in nuclei: For several reasons, the most productive future course to learn more about CLFV would use searches for $\mu^- + Z \to e^- + Z$, where *Z* is a nucleus and the muon in question is an atomic muon, usually in the *1-s* state, a process referred to as $\mu - e$ conversion in the nucleus *Z*. As already mentioned, it seems exceedingly challenging to improve the ability to hunt for $\mu \to e\gamma$ beyond the aspirations of the currently running MEG experiment. However, the same is not true of $\mu - e$ conversion in nuclei. Scientific groups around the world (especially in the US and in Japan) have confirmed that, with the right beam and adequate resources, it is possible to improve the sensitivity to $\mu - e$ conversion in nuclei by four or even six orders of magnitude. More important, searches for $\mu - e$ conversion in nuclei are, in general, sensitive to more types of new physics than are those for $\mu \to e\gamma$. Furthermore, models that predict the branching ratio of $\mu \to e\gamma$ to be larger than the normalized rate for $\mu - e$ conversion in nuclei predict the ratio of the normalized rates to be of order 300. This is a very robust statement and virtually independent of the new physics model. Hence, a search for $\mu - e$ conversion in nuclei that is, in absolute terms, more than 300 times more sensitive than a $\mu \to e\gamma$ search will necessarily be more sensitive to new physics, regardless of its nature.

Currently, searches for $\mu - e$ conversion in gold have excluded the normalized rate to be less than 7.0×10^{-13}. Two proposals, Mu2e at Fermilab and COMET at J-PARC in Japan, now aim at single-event sensitivities of order 10^{-17}. They will rely on stopping negative muons μ^- on a target and observing an electron with energy equivalent to the muon mass plus its binding energy. These searches are virtually background free as long as the electron energy resolution is good enough to rule out final-state electrons from muon decay in orbit. Backgrounds due to contaminants (mostly pions) in the muon beam can be dealt with by pulsing the muon beam to deliver all muons in one shot, leaving enough time for pions and kaons to decay before conducting the search.

Project X would make possible two distinct scenarios. If the next round of $\mu - e$ conversion experiments observe CLFV, the muon fluxes available with Project X would allow precision studies of CLFV with hundreds of $\mu - e$ conversion events, making possible the study of the rate for $\mu - e$ conversion in different nuclei and adding significantly to our understanding of the physics behind CLFV. If, however, the next round of $\mu - e$ conversion experiments finds no hint for CLFV, experiments with Project X could reach single-event sensitivities of 10^{-19} or beyond, given the development of an appropriate muon beam with a pulsed time structure, high purity and narrow beam-energy spread to allow for a thinner stopping target. To achieve these goals, physicists are now considering ideas using a muon storage ring installed in the muon beam line.

In summary, searches for CLFV and precision studies of muon properties are key to advancing the understanding of fundamental questions of 21st-century particle physics. They will play a critical role in revealing the source of neutrino masses and other related phenomena, including leptogenesis. They are complementary to direct searches at the energy frontier and to precision measurements in the quark sector. In the event that new particles are all very heavy and beyond the reach of the LHC, CLFV searches are among a handful of particle physics means available to explore nature at the smallest scales.

Nuclear Physics

Minute violations of the fundamental symmetries of nature can lead to measurable low-energy phenomena. For example, physicists expect that the CP-violating mechanism required to explain the matter-antimatter asymmetry in the universe will give rise to permanent electric dipole moments (EDMs) for particles in that sector that are far larger than the Standard Model predicts. Similarly, the weak interaction between electron and nucleon induces a feeble parity mixing in the electronic wave functions. The possible presence of interactions outside the assumed structure of the weak interaction will affect the angular correlations between emitted particles.

These observable phenomena offer access to possible physics beyond the Standard Model. They can often best be measured in specific radioactive nuclei tailored to enhance or isolate the sought effect. The following selected examples would greatly benefit from the availability of an intense radioactive ion source or an ultra-cold neutron source, both based on Project X.

Permanent electric dipole moments of fundamental particles like neutrons, electrons or neutral atoms, violate both parity and time reversal symmetry. Standard Model predictions for these EDMs lead to extremely small values, typically many orders of magnitude below current experimental limits. However, extensions of the Standard Model, such as supersymmetric models, predict much larger EDMs, and the existing experimental EDM limits already place stringent constraints on these models. EDM experiments provide an ideal opportunity for searches of physics beyond the Standard Model with minimal Standard Model physics background.

Currently, experimental efforts strive to improve the sensitivity of EDM searches by employing new experimental techniques to reduce the influence of systematic uncertainties. They also select nuclear or atomic systems with special properties that enhance the EDM signal. For example, experimental searches of nuclear EDMs currently explore high Z, octopole deformed nuclei like ^{225}Ra or ^{223}Rn, which benefit from a two-to-three order-of-magnitude enhancement of sensitivity over the previously best measured case of ^{199}Hg. However, those isotopes are unstable, and the availability of sufficient production yields will be a major issue in the future since the experiments will be largely limited by statistics. Likewise, novel approaches for electron EDM searches will use certain high-Z elements like Francium or, alternatively, specific polar molecules. In parallel, next-generation neutron EDM experiments are aiming to employ new intense ultra-cold neutron sources combined with refined experimental setups that provide better control over external magnetic and electric fields.

It is important to note that EDM measurements on different systems, that is, neutron, electron and nuclei, are highly complementary. When experimenters find a nonzero EDM in one system, it will require measurements on the other systems to elucidate the sources of the underlying T-violating processes. The ability of a facility based at Project X to deliver the highest yields of all these candidates strongly enhances the physics reach.

Experimenters have measured to better than a percent accuracy the parity mixing in the electronic wave function created by the weak neutral-current interaction between electrons and the nuclei they surround in Cesium atoms. This heroic measurement provided the most accurate value for the Weinberg angle at low momentum transfer. Theoretical uncertainties in atomic physics corrections limit the accuracy of this measurement. A natural path to improving it involves a measurement on trapped Fr isotopes, which have an 18-fold higher sensitivity to this effect. For this isotope, the ratio of measurements on both neutron-rich and neutron-deficient isotopes would still yield a larger signal than that in Cs while eliminating the atomic physics correction uncertainties. The next leading source of uncertainty would come from knowledge of the neutron distribution in these nuclei, but work at Jefferson Lab on ^{208}Pb and other low-energy measurements will reduce these uncertainties to the required level. A steady-state trapped Fr atom cloud of about 10^8 atoms would provide a counting rate comparable to the 10^{13} atoms /cm^2/s atomic beam used in the Cs experiment. A low-energy beam of 10^{10}-10^{12} Fr atoms/s injected into optical traps can provide this cloud. This quantity would be readily available at a facility based on a 500 kW 2-3 GeV proton linac. The Cs experiment also obtained the first positive indication of the existence of a nuclear anapole moment, albeit with a value inconsistent with predictions. The larger expected anapole moment in Fr and the higher sensitivity should yield a much-improved value that will help resolve this inconsistency and yield more reliable meson parity-nonconserving coupling constants.

Finally, beta-decay experiments looking at angular correlation between the emitted leptons, in both nuclei and neutron decays, are very sensitive to scalar and tensor couplings induced by physics beyond the Standard Model. Some extensions to the Standard Model, such as the minimal supersymmetric model, indicate that effects may be present at essentially the current experimental limits. Trapped radioactive atoms and ultra-cold neutrons have unique advantages for such measurements, because they can be stored, essentially suspended at rest in vacuum, and 100 percent polarized. The availability of many different decaying systems allows optimization of the sensitivity to specific interactions. The intense yields expected from a facility based on Project X are critical for this program.

Project X at the intensity frontier would also enable a broader program, centered on the radioactive ion and ultra-cold neutron production facilities. This includes topics such as neutron-antineutron oscillations, precise determination of the neutron lifetime and fifth-force searches.

Facility requirements/performance

The key enabler for this program is a reliable continuous wave high-intensity (~500 KW) 2-3 GeV proton beam.

For isotope production, proton spallation of ^{232}Th targets gives very prolific in-target yields of essential isotopes in the Rn, Fr, and Ra region of the periodic table. At a beam power of 500 kW, the isotope ^{225}Ra is produced in target at a rate of over 10^{13}/s. This is 25,000 times the yield provided by radioactive sources of this isotope, which are the basis of the present generation nuclear EDM experiment.

Ultra-cold neutron production can be designed so that neutrons can be delivered simultaneously both to those experiments that need maximum UCN density and to those that need maximum flux. Sources that produce a UCN density up to 10^5/cm^3 or a UCN flux greater than 10^8/s could be realized at Fermilab.

Project X can be the basis of a world-leading capability with an integrated, optimized source of both UCN and essential radioisotopes. Continuous wave proton beams totaling ~500 kW at ~2-3 GeV can be shared in this facility to enable both classes of research.