Project X Experiments
Supporting Document

Accelerator based experiments at the Intensity Frontier are now poised to make major advances toward understanding some of the most fundamental scientific questions of our time: the origin of mass, the origin of matter, and the origin of our universe. Project X will be a unique facility for the exploration of Intensity Frontier phenomena – the combination of multi-MW beam power available at a variety of energies, beam formats tailored to the needs of individual experiments and recent advances in detector technologies will enable a suite of experiments unrivaled in the world. The principal strength of the Project X experimental program is that it represents a broad-band assault with multiple probes of mass-scale reach beyond foreseeable colliders and sensitivities beyond competing initiatives at intensity frontier facilities world-wide.

The full Project X physics program supports world-leading experiments utilizing neutrinos, muons, kaons, nucleons, and nuclei. A staged implementation plan for Project X has been developed, featuring compelling physics opportunities with each of these probes at every stage. Here we highlight the opportunities at Stage 1, with commentary on expanded reach with later Stages.

The accelerator configuration and performance parameters for all Project X Stages are described in (Project X Performance by Stage). The heart of Project X Stage 1 is a new superconducting 1000 MeV linac that replaces the aging 400 MeV conventional linac in the Fermilab accelerator complex. Stage 1 will increase the Main Injector beam power from 700 kW to 1200 kW, the 8 GeV Booster beam power available to the short-baseline neutrino experiments from ~15 kW to 42 kW, and will serve as a powerful innovative proton driver for an upgrade of the Fermilab Muon Campus. This upgrade can be realized with the new linac operating at 100 kW with a 10% duty factor. The core superconducting technology of the new linac can support a very high beam duty factor (continuous wave or CW) and much higher beam power, 1 MW at 1000 MeV, which could be realized with a marginal (15%) increase in cost associated with higher RF power and cryogenics. A megawatt CW linac would open the door to an even broader research program for U.S. particle physics. In particular, a megawatt CW linac could support a world-leading program of electron, nucleon, nuclear, and atomic electric dipole moment (EDM) research and nucleon instability research through neutron-antineutron oscillation experiments. With the addition of a compressor ring to optimize proton pulse timing the megawatt linac could also provide a world-class decay-at-rest neutrino source for next generation short-baseline experiments. The new megawatt linac can also support an important program of materials research and R&D for high reliability proton drivers and targetry necessary for energy applications based on accelerator driven systems .

The possibility of leadership-level funding from India could allow Stage 2 to be built at the same time as Stage 1. Realizing Stage 2 of Project X would dramatically enhance the physics reach of the rare processes program, adding 3 MW beam power at 3 GeV to the Stage 1 capabilities, and extending high power (1200 kW) Main Injector operations down to 60 GeV – this could significantly improve the LBNE neutrino energy spectrum. At Stage 3 the Main Injector beam power is doubled, to 2400 kW over the entire energy range 60-120 GeV, and the 8 GeV Booster will be retired after more than a half-century of service.

Most of the material presented in this document if drawn from the recent of the Project X Physics Study (PXPS), which was held at Fermilab June 14–23, 2012, and attracted over 200 participants [2]. In advance of the 2013 Community Summer Study the Physics Study will continue to develop the physics case for all three stages of Project X in more detail. This document is an abbreviated summary of the broad program discussed at PXPS. The research program enabled by the full scope of Project X broadly attacks central issues in the field today: New physics at the electroweak scale and beyond, origins of flavor, and origins of matter-antimatter asymmetry. Just one example of the joint power of LBNE and Project X is the comprehensive campaign with EDM, neutrino and quark probes to crack the mystery of matter-antimatter asymmetries in our world, which are critical to the questions of baryogenesis and leptogenesis. In addition, the many experiments enabled by Stage 1 of Project X and described here substantially broadens the Fermilab research program in the early phase of LBNE.

Neutrino Experiments

The tremendous progress in neutrino physics over the past two decades has shown that neutrinos can be a precision tool for investigating the origin of the �lavor structure of elementary particles and for learning about fundamental aspects of cosmology and astrophysics. The fundamental questions that can be answered by an accelerator-based neutrino program include:

- **What is the origin of the flavor structure of elementary particles?**

  Our current understanding of flavor in elementary particle physics is reminiscent of chemistry in the late 19th century: The periodic table of the elements was known, but the origin of the observed similarities between different elements was not. Similarly, in particle physics, we do not know why elementary particles appear in three generations, and we do not understand the origin of their masses and mixing patterns. Many theoretical concepts and models exist to shed light on these mysteries, but discriminating between them and developing them further requires experimental input. In particular, a common feature of most models of flavor is that they predict specific relations among several masses or mixing angles. Testing these relations—or uncovering completely new ones—requires measurements of the relevant parameters with the highest possible precision.

  Long-baseline neutrino experiments are the optimal tools for the precision measurement of the atmospheric mixing parameters θ_{23} and $|\Delta m^2_{23}|$ and the CP-violating phase δ_{CP}. A neutrino factory could also provide the highest achievable precision on θ_{13}. Moreover, long-baseline neutrino experiments can make an important contribution to the determination of the neutrino mass hierarchy, sgn(Δm^2_{23}), which is an important discriminator between models of flavor.

- **Do leptons violate the CP symmetry?**
  This question is of particular interest in the context of leptogenesis [3, 4], one of the leading mechanisms for understanding the matter–antimatter asymmetry in the universe in the context of the seesaw mechanism. While is not possible to conclusively prove or disprove leptogenesis in a model-independent way with the currently achievable neutrino energies, the detection of leptonic CP violation in an oscillation experiment would be a strong hint for its existence because, generically, CP violation at the low scale and at the seesaw scale are related.

- **Are there more than three neutrino species?**
  Currently, there are several yet inconclusive results from short-baseline neutrino oscillation experiment, which can be interpreted as hints for the existence of a fourth neutrino flavor [5]. There is strong interest in the community for investigating these hints further, and an accelerator based program would provide the highest sensitivity and maximum long-term versatility.

- **Are there new effects in neutrino interactions with matter?**
  While the Standard Model provides a good description of neutrino interactions so far, it is possible that there are new, sub-leading effects that modify neutrino interactions. New flavor-violating or flavor non-universal interactions are particularly interest in the context of neutrino oscillation experiments, because they could either modify the reactions through which neutrinos are produced and detected or lead to new MSW-type matter effects [6, 7]that would affect the oscillation pattern.

Neutrino Experiments: Opportunities with Stage 1 of Project X

The physics reach of accelerator based neutrino experiments depends strongly on the energy and number of recorded neutrino interactions, which is in turn determined by the proton driver beam energy, beam power, detector mass, and running time. Optimizing the neutrino research program involves finding the ideal balance between these parameters, which are both individually and collectively resource limited.

The increased Main Injector beam power of Project X Stage 1 presents an opportunity to broaden this optimization space by enabling a productive long-baseline program to start with reduced detector mass or by reducing the running time required to reach a sensitivity milestone. As mentioned in the introduction, leadership-level funding from India may offer an opportunity for a simultaneous step forward on Stages 1 and 2 of Project X which would support further optimization of the LBNE neutrino energy spectrum while maintaining high beam power. Project

X Stage 1 also dramatically increases the 8 GeV beam power available to short baseline neutrino experiments, further broadening the optimization space of the Fermilab neutrino physics program.

In view of this, the optimum strategy for a phased neutrino program would be to interleave upgrades to the detector and the accelerator complex. For instance, the program could begin with Phase 1 of LBNE and an evolution of the short-baseline program followed by Stage 1 of Project X, which would enable both programs to increase their rate of data taking in order to improve sensitivities, or to proceed from first hints for a new phenomenon (for instance leptonic CP violation) to $>3\sigma$ evidence, and on to establishing discoveries with $> 5\sigma$ measurements. The progress of such an interleaved program in pursuit of leptonic CP violation is illustrated in Fig. 1.

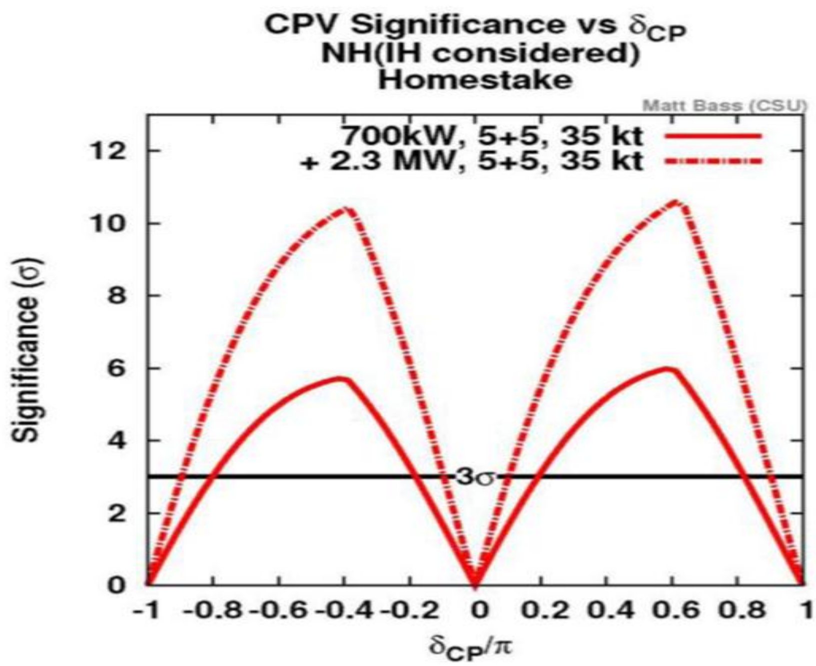

Figure 1: Evolution of LBNE sensitivity with Project X Stages. (Courtesy Matt Bass, Colorado State Univ.)

<u>Muon Experiments</u>

Muons offer a unique window into new physics effects in the charged lepton sector. They are light enough to be copiously produced, yet sufficiently massive to be sensitive to physics beyond the standard model. Despite being unstable, the muon lifetime is long enough to allow very precise measurements to be made. The precision possible in measuring properties such as the magnetic or electric dipole moments or the rate of rare processes means that even if new physics is so weakly coupled to the standard model or so very heavy it would have escaped discovery at the LHC, it could still be discovered in muon experiments at Project X, *e.g.*, $\mu \to e\gamma$, $\mu\mathrm{A} \to e\mathrm{A}$,

$\mu \rightarrow 3e$, *etc*. Furthermore, as this partial list demonstrates, there are many ways in which new physics can feed into muon physics and there is considerable interplay between each experiment since particular models predict different combinations of effects.

For instance, one class of operators that can be generated at the loop level from interactions with a new heavy state are the dipole operators. In some models, *e.g.*, minimal supersymmetry [8, 9], the size of these operators is related; in other models, they are not. The CP conserving operator contributes to $g-2$ of the muon, the CP violating to the muon electric dipole moment and the flavor violation to $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ conversion, and $\mu \rightarrow 3e$. These last three processes, which Project X is ideally suitedto pursue, may also receive contributions from tree level exchange of massive particles, such as leptoquarks. The high rate of stopped muons achievable with the Project X beam potentially allows a 5–6 order of magnitude improvement in the sensitivity to $\mu \rightarrow e$ conversion. Furthermore, the flexibility of the facility will allow this rate to determined for multiple target elements. This massive improvement in the bound translates into probing scales of 10^4 TeV. Similarly, there is potential to improve the sensitivity in $\mu \rightarrow 3e$ by 3–4 orders of magnitude.

In some supersymmetric models, the symmetry responsible for giving the dark matter candidate, R-parity, is extended to be a continuous symmetry. In these models, the rate for $\mu \rightarrow e\gamma$ is severely suppressed, and $\mu \rightarrow e$ and $\mu \rightarrow 3e$ provide the most immediate probes of flavor violation in the slepton sector, with potentially sizable rates. The reach for these models at the LHC is also considerably reduced from traditional supersymmetric models. Furthermore, the sensitivity of Project X is so great that should no flavor violation be seen in these modes this class of supersymmetric models can be *ruled out* as a solution to the supersymmetric flavor problem [10]. In Randall-Sundrum models of warped extra dimensions, one expects contributions to both $\mu \rightarrow e\gamma$, through penguins involving Kaluza-Klein (KK) modes, and $\mu \rightarrow e$, through tree-level KK exchange. Together these two constraints give a lower bound on the KK scale [11] that is already close to the LHC reach of the LHC.

A recent puzzle has emerged about the size of the proton [12], which appears to be considerably smaller when determined from binding energy differences in muonic versus electronic hydrogen. A very exciting explanation of this discrepancy is in terms of new contributions to the two-photon interaction with the proton. This interaction can be probed directly be using the Project X beam to scatter $\mu^{\pm}$ off of protons in a target.

In addition to the immediately available experiments of $g-2$ and $\mu \rightarrow e$ there is strong motivation from many models of new physics to also search in other lepton flavor violating modes such as $\mu^+ e^- \rightarrow \mu^- e^+$, $\mu^- N \rightarrow \mu^+ N'$, $\mu^- N \rightarrow e^+ N'$, and to search for CP violation through the muon electric dipole moment.

<u>Opportunities for Muons with Stage 1 of Project X</u>

Stage 1 of Project X dramatically increases the beam power to the Fermilab muon program with no impact on Main Injector neutrino operations. In particular, the 8 GeV beam power available to the $g-2$ program can be tripled, enabling a measurement of $g-2$ with μ^- with precision comparable to that of the μ^+ $g-2$ measurement in the pre-Project X era.

The 1-GeV CW linac of Stage 1 will serve as a greatly improved driver for the Mu2e program by providing much better beam timing characteristics (10 ns vs. 200 ns wide proton pulses), no antiproton background, identical muon yield per Watt of beam power (as compared to 8 GeV), and the potential for a tenfold of more increase in the beam power delivered to the experiment. Collectively, these improvements can improve the sensitivity of the Mu2e program by an order of magnitude or better.

Kaon Experiments

Continuation of the Fermilab kaon physics research program is being pursued with the ORKA initiative. The ORKA experiment is driven with Main Injector beam and will likely commence running during the Proton-Improvement-Plan (PIP) era of Main Injector operations. The initial principal goal of the ORKA experiment is precision measurement (5%) of the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$ [13], which can be realized with five years of Main Injector beam in the PIP era or three years of Main Injector beam in the Project X Stage 1 era. This measurement would be one of the most incisive probes of quark flavor physics this decade. Its dramatic reach for uncovering new physics is due to several important factors:

- The $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio is highly suppressed in the Standard Model below the 10^{-10} level (less than 1 part per 10 billion) [14]. This suppression allows physics beyond the Standard Model to boost the branching fraction with enhancements of up to a factor of five above the Standard Model level.
- The Standard Model prediction for the $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction is broadly recognized to be theoretically robust at the 5% level [15]. Only a precious few accessible loop-dominated quark processes can be predicted with this level of certainty.
- The branching ratio is sensitive to most new physics models that extend the Standard Model to solve its considerable problems [16].

Taken together, these factors permit a 5σ discovery potential for new physics even for enhancements of the branching ratio as small as 35%. Such sensitivity is unique in quark flavor physics and allows probing of essentially all models of new physics that couple to quarks within the reach of the LHC. Furthermore, a high precision measurement of $K^+ \to \pi^+\nu\bar{\nu}$ is sensitive to many models of new physics with mass scales well beyond the direct reach of the LHC. This exciting opportunity has been recognized by planning bodies in US High Energy Physics (HEPAP and P5), and CERN is now pursuing a measurement at intermediate sensitivity with the NA62 experiment. In recognition of this physics reach the Fermilab Director has recently granted scientific approval to the ORKA proposal. The collaboration is working with the laboratory, US agencies, and international agencies to advance the ORKA experiment.

Process	Current	ORKA	Comment
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events	
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ at 90% CL	$< 2 \times 10^{-12}$	$K^+ \to \pi^+ \nu\bar{\nu}$ is a background
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \pi^0 X^0$	$\lesssim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \to \mu^+ \nu_{heavy}$	$< 2\text{–}10 \times 10^{-8}$	$< 1 \times 10^{-10}$	150 MeV $< m_\nu <$ 270 MeV
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$	
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events	
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$	
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 4\text{–}50 \times 10^{-9}$	depending on technique
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

Table 1: Breadth of the ORKA program at Stage 1 of Project X

<u>Opportunities for Kaons with Stage 1 of Project X</u>

The Project X Stage 1 kaon physics program will be driven by the increased power of Main Injector proton beam delivered to the ORKA research facility. The ORKA research program includes many measurements beyond precision measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction such as heavy neutrino searches, dark photon searches, and many other processes sensitive to physics beyond the standard model [17]. Further, a very high statistics sample (> 1000) of events enables precision measurement of the form-factor which is a powerful tool to elucidate the nature (e.g., scalar, vector, tensor couplings) of new physics that can affect the branching fraction. Stage 1 of Project X will boost the sensitivity of this entire program whose breadth is summarized in Table 1.

The ORKA facility will be the highest intensity source of charged kaons available world-wide in both the PIP and Project X Stage 1 era. Following completion of the ORKA research program the facility can be used to drive other high sensitivity charged kaon experiments, such as the TREK experiment which is designed to search for and measure the anomalous polarization of muons induced by new physics in $K^+ \to \mu^+ \pi^0 \nu$ decays. The initial phase of the TREK program is being pursued at JPARC, but reaching the ultimate sensitivity of the TREK technique will require kaon sources as bright as the ORKA facility in the Stage 1 of Project X which is beyond the projected reach of JPARC.

<u>Electric Dipole Moments</u>

Electric dipole moments (EDMs) describe the interaction of the spin of a particle with an external electric field. Such an interaction breaks the discrete symmetry of time reversal T and therefore, according to the CPT-theorem, it can generate signals of CP violation, i.e., the violation of the product of charge conjugation C and parity P. The Standard Model (SM) without neutrino masses contains two sources of CP violation: the QCD theta term and the phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. As summarized in Table 2, SM predictions for EDMs based only on the CKM phase lead to values at least five orders of magnitude below the current experimental sensitivities and, thus, leave plenty of discovery potential for new physics. Ongoing and planned EDM experiments are mainly statistically limited. Already at Stage 1 of Project X an unmatched increase in sensitivity to EDMs could be achieved that would allow to probe broad classes of new physics models that contain new sources of CP violation [22, 23].

EDMs	SM	current limit	Project X
electron	$\sim 10^{-38} e$ cm	$1.0 \times 10^{-27} e$ cm	$\sim 10^{-30} e$ cm
muon	$\sim 10^{-35} e$ cm	$1.1 \times 10^{-19} e$ cm	$\sim 10^{-23} e$ cm
neutron	$\sim 10^{-31} e$ cm	$2.9 \times 10^{-26} e$ cm	$\sim 10^{-29} e$ cm
proton	$\sim 10^{-31} e$ cm	$6.5 \times 10^{-23} e$ cm	$\sim 10^{-29} e$ cm
nuclei	$\sim 10^{-33} e$ cm (^{199}Hg)	$3.1 \times 10^{-29} e$ cm (^{199}Hg)	$\sim 10^{-29} e$ cm (^{225}Ra)

Table 2: SM predictions and current and expected Project X Stage 1 limits on selected examples of EDMs

The search for EDMs in the era of the LHC should have high priority. If new physics is discovered at the LHC, EDMs will provide excellent probes to test the existence of possible new CP-violating phases beyond those present in the SM. In particular, EDMs are highly sensitive to additional sources of CP violation in the Higgs sector [24]. On the other hand, in the absence of any direct new physics signals at the TeV scale, searches for EDMs will have the potential to probe much higher scales as long as the new physics is assumed to contain sizable sources of CP violation. In fact, it is well known that the CP violation in the SM is not enough to explain the matter-antimatter asymmetry in the universe. Estimates in the SM lead to values for the baryon density that are many orders of magnitude smaller than observed. This strongly suggests the existence of new sources of CP violation beyond those already present in the SM, and EDMs constitute a unique toolkit to search for them. For example in the framework of electroweak baryogenesis in the minimal supersymmetric extension of the Standard Model, an explanation of the matter-antimatter asymmetry leads to lower bounds on EDMs that, as shown in Fig. 3, are up to two orders of magnitude below the current experimental limits. The sensitivities that can be achieved with Project X will allow us to probe essentially the entire parameter range of that framework and other related supersymmetric scenarios [25, 26, 27, 28].

There are various examples of EDMs that can be probed experimentally. EDMs of the proton, neutron, and deuteron are highly sensitive to the QCD theta term as well as the EDMs and chromo-EDMs of their constituent quarks. EDMs of paramagnetic atoms and molecules, i.e., systems with an unpaired electron, are mainly sensitive to the EDM of the electron. EDMs of diamagnetic atoms and molecules, i.e., systems with paired electrons, mainly probe the chromo-EDMs of quarks. Probing all these systems therefore gives valuable complementary information. If a nonzero EDM in one system were to be observed in the future, measurements of the other systems would be required to resolve the underlying origin of CP violation.

EDM measurements with Project X Stage 1

Measurements of the neutron EDM use ultra-cold neutrons. At Project X Stage 1, a 1 GeV proton spallation target coupled to a cold or ultra-cold moderator has the potential to generate ultra-cold neutron densities 50 times larger than what can be currently achieved. This would allow an increase in sensitivity to the neutron EDM by $\sim$ 3 orders of magnitude down to a level of 10^{-29} e cm.

A precise measurement of the proton EDM can be done in an all-electric storage ring that may fit
into the former accumulator ring at Fermilab. A highly polarized (> 80%) proton beam is required, with an intensity of $\sim 4 \times 10^{10}$ particles per cycle that is stored for $\sim 10^{3}$ sec. The experiment could start already in the pre-Project X era and later profit from the high quality beams provided by Project X. The experiment aims at a statistical sensitivity for the proton EDM of $d_{\mathrm{p}} \sim 10^{-29}$ e cm, which corresponds to an improvement by six orders of magnitude compared to the present limit. This aim is also comparable to the possible reach of a neutron EDM experiment at Project X.

Measurements of the proton and neutron EDMs with the proposed precision can by themselves either probe CP-violating phases at the TeV scale down to $\sim 10^{-5}$ or constrain the QCD theta term down to the level of 0.3×10^{-13}. Moreover, the information from the proton and neutron EDMs complement each other. While the neutron and proton EDMs depend in a very similar way on sources of CP violation beyond the SM, the QCD theta term enters with a different sign. Correspondingly combining the information from proton and neutron EDMs allows to constrain new sources of CP violation and the QCD theta term simultaneously, or—if a nonzero EDM is seen—to disentangle the CP-violating source.

Several para- and dia-magnetic atoms and molecules have strongly amplified sensitivities to EDMs of elementary particles. Prime examples are Francium and Thallium atoms that have enhanced sensitivity to the electron EDM with enhancement factors of several hundreds to a thousand. Nuclei with large quadrupole and octupole deformations like Radon and Radium on the other hand show particular high sensitivity to the constituent quark EDMs and chromo-EDMs. The EDM of ^{225}Ra for example is at least 2–3 orders of magnitude more sensitive than the EDM of Mercury. The sensitivity enhancement factors that certain paramagnetic and diamagnetic systems offer are subject to considerable theoretical uncertainty. Different calculations differ by factors of a few, making it harder to interpret the experimental results as constraints on new sources of CP violation if no signal is observed. On the other hand, due to the large enhancement factors, such systems are ideal discovery channels for nonzero EDMs.

To study the EDMs of atoms and molecules at Project X, a high intensity Isotope Separator On-Line (ISOL) type facility is required to separate isotopes that are produced from proton spallation. The predicted yields of isotopes like Radon, Francium, and Radium from a 500 kW to 1 MW proton beam with an energy of 1 GeV on a Thorium target are 100 to 1000 times larger than the yields of currently running facilities. For example, the estimated yield for ^{225}Ra of $10^{13}s^{-1}$ leads to a sensitivity to the ^{225}Ra EDM at the level of 10^{-28}–10^{-29} e cm. This corresponds to an increase in sensitivity to quark chromo-EDMs by 2-3 orders of magnitude with respect to current measurements of the EDM of ^{199}Hg atoms. The expected yield for ^{211}Fr of $10^{13}s^{-1}$ would allow to improve the sensitivity to the electron EDM by 3 orders of magnitude with respect to the current bound that is inferred from the measurement of the EDM of YbF molecules. These unmatched sensitivities are required to scrutinize models of electroweak baryogenesis and will put to the test new physics models that contain new sources of CP violation even far above the TeV scale.

In summary, new sources of CP violation beyond those present in the SM are required to explain the matter-antimatter asymmetry of the universe and are naturally expected in models of new physics. EDM measurements provide a unique toolkit to test such possible new sources of CP violation. Project X will allow to extend current sensitivities by a few to several orders of magnitude thereby probing large unexplored regions of new physics parameter space. In particular, it will provide a conclusive test of supersymmetric models of Electroweak Baryogenesis.

Neutron-Antineutron Oscillations

A timely observation of neutron-antineutron oscillations could constitute the first direct evidence for baryon-number violation and give new insights into the scales relevant for quark-lepton unification and neutrino mass generation [29]. An experiment sensitive to free n-$\bar{n}$ oscillations with a period of 10^{10}-10^{11} s, which would decisively test theories of baryogenesis and of the origin of neutrino mass, may be feasible with a 1 MW spallation target for slow-neutron production at Project X. As a complement, the large-volume liquid-argon detectors planned for long-baseline neutrino experiments in the framework of Project X could significantly advance the search for n-$\bar{n}$ within nuclei.

The search for neutron-antineutron oscillations may illuminate two of the great mysteries of particle physics and cosmology: the great stability of ordinary matter and the origin of the preponderance of matter over antimatter in the universe. Processes that violate baryon number and lepton number must be highly suppressed, but they must be present if the observed matter excess evolved from an early universe in which matter and antimatter were in balance [30]. The primitive interactions of quantum chromodynamics and the electroweak theory conserve baryon number B and lepton number L, but we have not identified a dynamical principle or symmetry that compels conservation of either baryon number or lepton number. The discovery that neutrino species mix, which demonstrates that individual (e, μ, τ) lepton numbers are not conserved, leaves open the possibility that overall lepton number is conserved. The observation of neutrinoless double-beta decay would establish L nonconservation.

Theoretical analyses of the electroweak theory have identified a nonperturbative "sphaleron" mechanism that breaks both B and L, but preserve $B - L$ [31]. The sphaleron process is unobservably rare under normal conditions in the present (cold) universe, but might have yielded significant B and L violations in the hot early universe. It is unclear whether such electroweak baryogenesis can give a coherent account of the observed matter excess. Other mechanisms for B and L violation arise in unified theories of the strong, weak, and electromagnetic interactions that place quarks and leptons in extended multiplets and imply (highly suppressed) quark ↔ lepton transitions among their primitive interactions. The implication of proton decay in these theories [32] has drawn significant experimental attention because the first SU(5) and SO(10)-based theories set attainable targets and suggested a candidate explanation for the origin of matter. Within unified theories, the $\Delta B = 1$ process proton decay probes new physics at an energy scale of 10^{15} GeV, while the $\Delta B = 2$ phenomenon of n-$\bar{n}$ oscillations might implicate new physics not far above the TeV scale. Among models of new physics are examples that forbid proton decay but predict neutron oscillations. Because the two phenomena probe different mechanisms, it is important to advance the search for baryon-number violation on both fronts.

A search for free $n \to \bar{n}$ transitions using a cold neutron beam from the research reactor at Institut Laue-Langevin in Grenoble set a lower bound on the oscillation time of $\tau > 8.6 \times 10^7$ s [33]. In one year of operation, the experiment recorded zero candidate events and no background. Large underground detectors built for proton-decay searches and neutrino-oscillation studies are also sensitive to $n \to \bar{n}$ transitions within nuclei. Such bound-neutron oscillations are greatly suppressed by the different potentials experienced by neutrons and antineutrons in the nuclear environment. A Super-Kamiokande bound on the nuclear oscillation time [34], $\tau_A > 1.89 \times 10^{32}$ years in oxygen corresponds to free-neutron oscillation times in the range 2.4–3.5×10^8 s, depending on the theoretical model of the nuclear environment. The Super-Kamiokande limit was derived from 24 observed candidate events with estimated background of 24.1 events from atmospheric neutrino interactions in the detector. This atmospheric-neutrino background makes further improvement of $n \to \bar{n}$ searches in water-Cherenkov detectors larger than Super-Kamiokande extremely challenging and would seem to make it impossible to establish a discovery.

Two recent developments heighten the interest in the search for n-$\bar{n}$ transitions [35]. First, the discovery of neutrino masses that is implied by neutrino mixing has renewed interest in the seesaw mechanism to explain why neutrino masses are tiny compared with the charged-lepton masses. This picture requires Majorana mass terms, which break $B-L$ conservation by two units, just as $n \rightarrow \bar{n}$ transitions do. In a large class of gauge models, the neutrino Majorana masses lead directly to n-$\bar{n}$ oscillations. To generate neutrino masses in the required range naturally, the seesaw scale must lie below the Planck scale. Second, leptogenesis, a paradigm for understanding the preponderance of matter over antimatter, does not rely on proton decay as its essential ingredient, but generates a matter-antimatter asymmetry through the neutrino-mass seesaw. When the seesaw mechanism is embedded into unified theories that incorporate $B - L$ symmetry, the scale at which that symmetry is broken can be as low as the TeV scale. Even if the Majorana nature of the neutrino were established by detecting neutrinoless double beta decay, the observation of $n \rightarrow \bar{n}$ transitions might establish a common mechanism for the two processes. At the sensitivity available at Project X, an observation of $n \rightarrow \bar{n}$ oscillations would indicate that the small neutrino mass does not signal physics at the unification scale, but at a far lower scale.

The large-volume liquid-argon detectors planned for neutrino oscillation studies in connection with Project Xmay be able to conduct improved searches for n-$\bar{n}$ oscillations of neutrons bound in nuclei. In a large liquid-argon detector sited underground, precise vertex resolution might be exploited to reduce the atmospheric neutrino background that limits the performance of large underground detectors based on water-Cherenkov technology.

Prospects for an essentially background-free measurement using free neutrons are excellent. In the absence of a magnetic field (which would differentially shift neutron and antineutron energy levels) and in vacuum, the n-$\bar{n}$ oscillation probability grows as $P = (t/\tau)^2$, where t is the free-neutron observation time and τ is a characteristic oscillation time determined by new physics processes that induce $\Delta B = 2$ transitions. If the scale of the relevant new physics is around 10^4–10^6 GeV, as predicted by various theoretical models, the possible range of n-$\bar{n}$ oscillation time is $\tau \sim (10^9$–$10^{11})$ s. The figure of merit for a free-neutron $n \rightarrow \bar{n}$ search is $N_{\mathrm{n}} \times t^2$, where N_{n} is the number of free neutrons observed and t is the observation time. Any apparatus will involve the delivery of a high flux of free neutrons from the slow neutron source through a vacuum vessel (vacuum better that 10^{-5} Pa) with magnetic shielding (1 nT) to a 100-micron thin foil surrounded by an antineutron annihilation detector. A dedicated spallation neutron source at Project X can be optimized to produce slow neutrons and deliver them to an antineutron annihilation target with a precisely-defined vertex location by using modern neutron moderators and cryogenic technology. An increase in the delivery of slow neutrons to the annihilation target can be achieved by maximizing the phase space acceptance for neutron extraction around the cryogenic converter with advanced super mirrors, whose performance far exceeds what was available to the ILL-based experiment and represents the single most important contributor to an improved experimental sensitivity.

Any positive observation can be suppressed experimentally by breaking the near degeneracy of the neutron and antineutron states by applying a small magnetic field. The free-neutron approach has enormous potential in exploring the stability of matter: a limit on the free-neutron oscillation time $\tau > 10^{10}$ s would correspond to the limit on matter stability of $\tau_A = 1.6–3.1 \times 10^{35}$ years.

The same slow neutrons needed for a sensitive free neutron-antineutron oscillation search are also of potential interest for searches for the neutron electric dipole and other experiments. Existing slow neutron sources at research reactors and spallation sources possess neither the required space nor the access to the cold source needed to take full advantage of advances in neutron optics technology.

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