Physics Opportunities with Stage 1 of Project X

Wolfgang Altmannshofer, Marcela Carena, Patrick Fox, Stuart Henderson,
Stephen Holmes, Young-Kee Kim, Joachim Kopp, Andreas Kronfeld,
Joseph Lykken, Chris Quigg, and Robert Tschirhart

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1 Introduction

Interleaving phases of LBNE and Project X will enable pursuit of ever increasing sensitivity to neutrino mixing parameters. Stage 1 of Project X can also enable pursuit of several other physics opportunities in parallel. We survey here the research program for the first stage of Project X, which is technically advanced enough now to consider it at the same time as Phase 1 of the reconfigured LBNE. Most of the physics case for Project X has been discussed elsewhere, for example in Ref. [1], without factoring the program into the three stages of Project X. Here we aim to show how well known and compelling physics questions can be addressed with Stage 1 of Project X.

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. The accelerator parameters of the Project X Stage 1 complex are described below in Sec. 10. In short, Stage 1 will increase the Main Injector beam power from 700 kW to 1200 kW, the 8 GeV Booster beam power available to short-baseline neutrino experiments from 25 kW to 42 kW and 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 US particle physics. In particular, a megawatt CW linac could support a world-leading program of electron, nucleon, nuclear, and atomic 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 and support high power (1200 kW) Main Injector operation at 60 GeV which can significantly improve the LBNE neutrino energy spectrum.

Most of the material presented here is drawn from the recent meeting of the Project X Physics Study (PXPS), which was held at Fermilab June 14–23, 2012, and attracted over 200 participants [2]. Over the next twelve months, the PXPS will develop the physics case for all three stages of Project X in more detail. This appendix 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.

2 Neutrino Experiments

2.1 Physics Questions

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 flavor 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 $\delta_{\rm CP}$. 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, $\mathrm{sgn}(\Delta m^2_{23})$, 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, subleading effects that modify neutrino interactions. New flavor-violating or flavor-nonuniversal 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.

2.2 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. As shown in Sec. 10, 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.

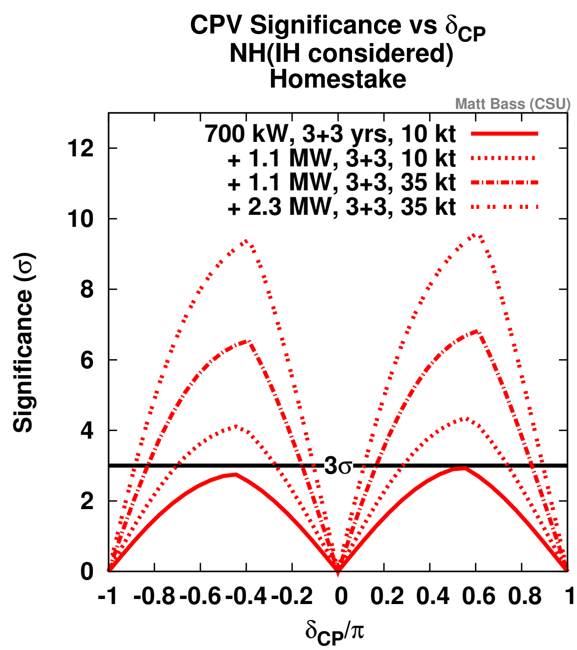

Figure 1: Evolution of LBNE sensitivity with Project X Stages. (Courtesy Matt Bass, Colorado State Univ.)

3 Muon Experiments

3.1 Muons as a probe of short-distance physics

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.*, $\mu \to e\gamma$, $\mu \to e$, $\mu \to 3e$, *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 $\mu \to e\gamma$, $\mu \to e$ conversion, and $\mu \to 3e$. These last three processes, which Project X is ideally suited to 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 $\mu \to e$ 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 $\mu \to 3e$ 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 $\mu \to e\gamma$ is severely suppressed, and $\mu \to e$ and $\mu \to 3e$ 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 $\mu \to e\gamma$, through penguins involving Kaluza-Klein (KK) modes, and $\mu \to e$, 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 $\mu \to e$ there is strong motivation from many models of new physics to also search in other lepton flavor violating modes such as $\mu^+e^- \to \mu^-e^+$, $\mu^-N \to \mu^+N'$, $\mu^-N \to e^+N'$, and to search for CP violation through the muon electric dipole moment.

3.2 Opportunities with Stage 1 of Project X

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 charateristics (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.

4 Kaon Experiments

4.1 Kaons as a probe of short-distance physics

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.

Table 1: Breadth of the ORKA research program. From Ref. [17].

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
$K^+ \to \pi^+\pi^0\nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+\pi^0X^0$	$\lesssim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+\gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \to \mu^+\nu_{heavy}$	$< 2\text{–}10 \times 10^{-8}$	$< 1 \times 10^{-10}$	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
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

4.2 Opportunities with Stage 1 of Project X

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.

5 Hadronic Physics Experiments

5.1 Mysteries in the Chemistry of Quarks

Quantum Chromodynamics is an elegant theory that accounts for the strongly-interacting dynamics of the Standard Model and the existence of mesons and baryons as confined composites of quarks. Lattice QCD has become a mature tool for predicting strong interaction physics with accuracies of a few percent, while perturbative QCD calculations match data from the Large Hadron Collider with similar precision. QCD accounts for 99% of the mass and most of the structure of ordinary matter, and predicts the existence of wonderfully exotic new states of matter at high temperatures and densities [18].

Yet in spite of decades of study many basic properties of QCD remain a mystery. QCD predicts exotic resonances such as glueballs whose existence has yet to be verified, while many unexpected resonances observed in experiments are not understood in the framework of QCD. Our current knowledge fails to explain the spin of the proton as well as many detailed questions related to the quantum properties of its quark and gluon constituents. Nor do we understand how the structure of the proton is modified when it is inside a nucleus, a basic missing link between QCD and nuclear physics. Last but not least, AdS/CFT duality tells us that much of the confining dynamics of QCD has an equivalent description in terms of string theory and extra-dimensional gravity, but these profound connections also involve some of murkiest areas of hadronic physics.

These important mysteries motivate a new generation of experiments aimed at hadronic physics. These fixed-target experiments will require intense beams of protons, pions, kaons, and neutrinos. The increasing beam power and flexibility of the Project X program, stage by stage, would enable a growing suite of hadronic physics experiments with unique capabilities that complement experiments planned elsewhere.

5.2 Finding clues to the mysteries with Project X Stage 1

Fermilab already has in place a strong experimental program for hadronic physics. The MINERvA experiment measures deep inelastic scattering of neutrinos from protons and neutrons in a variety of target nuclei, thus probing their valence and sea quark structure and addressing how proton constituents are affected by and related to nuclear binding. At the same time the SeaQuest experiment, scheduled to run from 2013-2015, will study very similar physics using Drell-Yan events induced by a Main Injector proton beam and a variety of targets. This combined program comes on the heels of previous experiments that raised many questions about the momentum distributions of quark constituents of bound nucleons, including the "EMC effect," which was not confirmed in Drell-Yan results.

Upgrades of these experiments during the first stages of Project X would provide the capability of making sufficiently detailed and precise measurements to conclusively resolve these puzzles and thereby illuminate the underlying physics. For MINERvA this would also require lighter targets and detector upgrades, and for SeaQuest the use of polarized targets. Since SeaQuest runs in some sense parasitically on the Main Injector neutrino program, even modest increases in the number of available MI protons can have a large effect on the physics potential for these measurements. A Project X era version of SeaQuest could improve by three orders of magnitude on the luminosity of the planned COMPASS experiment at CERN.

Heavy quark spectroscopy has enjoyed a golden age of interplay between theory and experiment, leading to many insights about QCD dynamics. During this same period the BaBar and Belle experiments discovered many unexpected states, as well as many states with unexpected masses [1]. These discoveries have revealed gaps in our understanding of confined QCD composites other than quark-model mesons and baryons. The plausible but as yet unconfirmed possibilities include glueballs (confined states of gluons alone), hydrids (confined states with both valence quarks and gluons), four-quark mesons, five-quark baryons, and hadronic "molecules" [19]. In general, light quark spectroscopy is less well understood than that of heavy quarks.

Glueballs provide a dramatic case in point of current challenges and opportunities. Recent advances in lattice gauge theory make it possible to compute the spectrum of glueballs with some confidence, as illustrated in Fig. 2, where the different resonances are labeled according to their J^{PC} quantum numbers. The experimental confirmation of the existence of glueballs has been held back by the fact that the lightest states will certainly mix with meson states of the same quantum numbers. However since not all combinations of J^{PC} values can occur for mesons, some of the heavier glueballs are pure exotics.

In AdS/CFT dual theories, the 2^{++} glueball is a massive graviton mode, while the 0^{++} and other glueballs correspond to the dilaton and other characteristic excitations of string theory [20]. While it is not believed that QCD has an exact gravity dual, there is strong evidence that most of the basic physical elements of confined QCD have a dual description in the dynamics of strings, gravity, and warped extra dimensions. Understanding these profound theoretical connections is contingent on getting better experimental handles on QCD spectroscopy, and motivates a new generation of experiments.

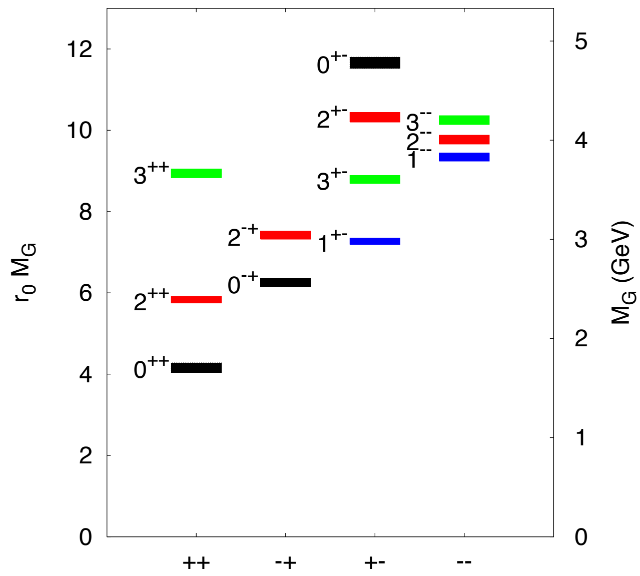

Figure 2: The spectrum of QCD glueballs from lattice QCD [21].

Enabled by the favorable proton economics of the first stage of Project X, this new generation of experiments could utilize kaon and/or pion beams originating from MI protons, using fixed targets to induce peripheral production of hadronic states. The experiments would be complementary to a Project X kaon program focused on rare decays. Besides the advantages of intense beams, these experiments would benefit from advanced detector technologies, allowing greatly increased reach to probe this physics. In the event that experiments elsewhere, such as the GlueX experiment at JLab, find evidence for hybrids or other exotic states of QCD. A Project X powered program at Fermilab would be even more compelling.

6 Electric Dipole Moments

6.1 Electric dipole moments as probes of new physics

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].

The search for EDMs in the era of the LHC should have high priority. If new physics is discovered at

Table 2: SM predictions and current and expected limits on selected examples of EDMs.

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)

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.

6.2 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 ~ 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 $\sim 10^3$ s. 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 $d_p \sim 10^{-29} e$ 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.

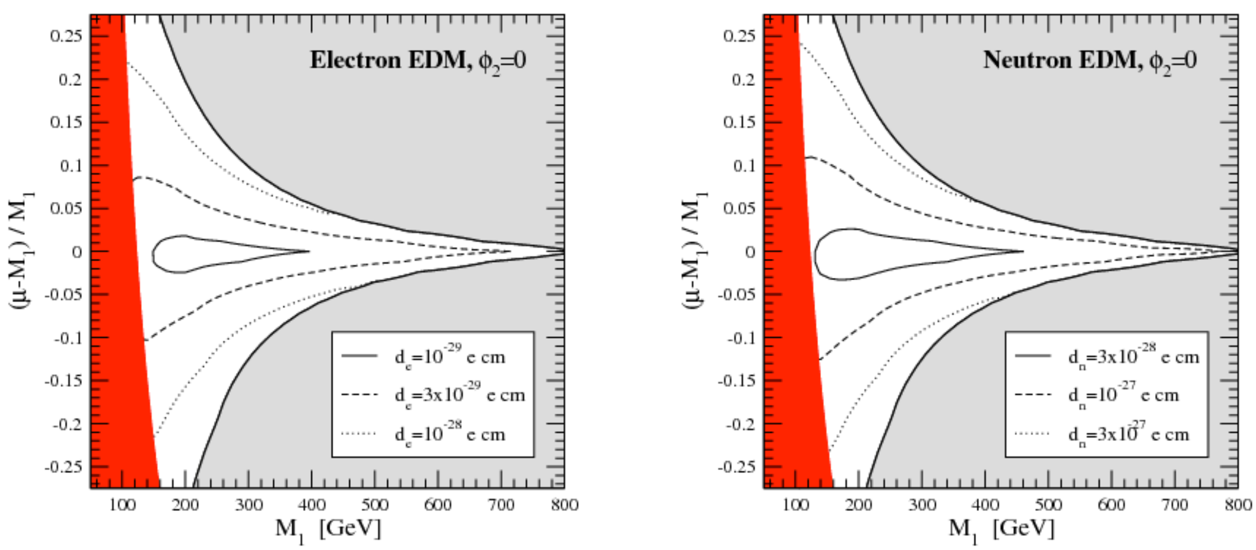

Figure 3: Predictions for EDMs in an MSSM scenario of electroweak baryogenesis. The contours show constant values of the electron EDM (left) and the neutron EDM (right) with the CP-violating phase set to the value giving the right baryon asymmetry. The red region is excluded by chargino searches at LEP; in the gray region the baryon asymmetry is too small even for maximal CP violation. From Ref. [26].

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 $10^{13}\,\mathrm{s}^{-1}$ 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 $10^{13}\,\mathrm{s}^{-1}$ 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.

7 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 $\leftrightarrow$ 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 $\times 10^8$ 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 $n \to \bar{n}$ 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 $n \to \bar{n}$ transitions might establish a common mechanism for the two processes. At the sensitivity available at Project X, an observation of $n \to \bar{n}$ 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 X may 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 $n \to \bar{n}$ search is $N_n \times t^2$, 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 supermirrors, 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 $\tau_A = 1.6$–3.1×10^{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.

8 Lattice QCD Calculations: Enabling Infrastructure for Project X

Many of the intensity-frontier experiments made possible with Project X Stage 1 entail an important theoretical uncertainty from hadronic effects. Fortunately, recent strides in lattice gauge theory [18] show that we have a tool to compute many of the transition matrix elements needed during all stages of Project X, including Stage 1.

Much of the precision success, so far, has been with mesons. For example, the simplest leptonic and semileptonic decays of pions and kaons have now been computed with total uncertainty below $\sim 1\%$. At this level, it becomes necessary to improve our understanding of isospin violation and the interplay of electromagnetic effects. For much of the Project X physics program, nucleon matrix elements are needed. For several reasons, these are not yet as precise. That said, increases in raw computer power and the resources allocated to lattice QCD suggest that nucleon matrix elements needed for the Project X physics program should be available in a timely way. More details on expected (US-based) resources for lattice QCD can be found in the USQCD Collaboration's whitepaper on flavor physics [36], prepared for the Intensity Frontier workshop [1]. In short, we expect lattice QCD to keep pace with the three stages of Project X.

8.1 Neutrino experiments

Lattice QCD can be used to calculate moments of the parton densities, which are measured in neutrino deep-inelastic scattering. At present, however, the hadronic effects in neutrino oscillations remain completely unexplored in lattice QCD. This situation could change, at least for matter effects, where one is interested in neutrino-nucleus scattering from moderately low energies, 0.5–5 GeV, as well as at high energies (for QCD) $>$ 5 GeV. In all cases, one has to reduce the problem to neutrino-nucleon scattering. At the high end, factorization techniques of perturbative QCD can be applied (ν DIS), but at the low end a direct calculation of the matrix elements would be helpful. Nuclear effective field-theory techniques can show how to incorporate nuclear effects [37].

8.2 Muon experiments

The two leading sources of theoretical uncertainty in the muon $g-2$ stem from QCD. The larger of these two comes from hadronic vacuum polarization (HVP), which can be measured from $e^+e^- \to$ hadrons and from τ decays. These approaches require little and moderate additional theory input, respectively. Unfortunately, their agreement is imperfect, sowing some controversy. Buoyed by the New $g-2$ Experiment at Fermilab (E989), several groups around the world are calculating the HVP with lattice QCD. It seems likely that competitive results will become available in a few years and, possibly, superior results in time for Project X Stage 1 [38].

The second largest theoretical uncertainty comes from light-by-light scattering. This contribution to $g-2$ is, at present, estimated with a combination of QCD constraints (e.g., low-energy theorems and asymptotics from the operator-product expansion) and models of QCD for $q^2 \sim m_\mu^2$ effects. A direct calculation from lattice QCD seems feasible in principle. At present, pioneering work is underway [38].

In $\mu \to e$ conversion, two hadronic contributions enter the theoretical formulae for the rate (in and beyond the SM) [39]. In the coherent contribution, one has quasi-elastic $\mu N \to eN$ scattering, where N is a proton of neutron. The needed matrix elements are of the kind routinely calculated in several studies of nucleon structure [40]. In the incoherent contribution, the released energy affects the whole nucleus. To apply lattice QCD here, one would first need an effective-field-theory framework to relate nucleonic matrix elements to the nuclear structure.

8.3 Kaon experiments

The power of rare decays such as $K^+ \to \pi^+\nu\bar{\nu}$ to discover new physics, or diagnose the identity of new particles expected to be observed at the LHC, will improve with better determinations of the of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$. At present, the theoretical uncertainties are $\sim$ 1% and $\sim$ 8%, respectively. With data from Belle and BaBar and better calculations of the $B \to D^{(*)}\ell\nu$ and $B \to \pi\ell\nu$ form factors, and prospects with proposed next-generation B factories are better still [36].

Apart from these parametrice uncertainties, the least-well understood contribution to $K^+ \to \pi^+\nu\bar{\nu}$ stems from long-distance charmed loops. Here again, lattice QCD calculations can help [41].

8.4 Hadronic physics

As discussed in Sec. 5, lattice QCD plays a central role in QCD spectroscopy. Recent work has moved beyond calculating masses of the lowest-lying states to explore the excited-state spectrum [42]. This work includes mixing effects (e.g., η-η'), hybrid mesons, and glueball decay characteristics.

As with neutrino deep-inelastic scattering, lattice QCD can be used to calculate moments of distributions measured in muon deep-inelastic scattering and in Drell-Yan production. This is an active, on-going program, encompassing also more ambititious, related calculations, such the the generalized parton densities.

8.5 Electric-dipole moments

Many groups are calculating the matrix elements needed to understand nucleon EDMs, with an eye to both the strong CP problem and BSM CP violation [40]. As noted in Sec. 6, these calculations, combined with measurements of the neutron and proton EDMs, will distangle strong and BSM CP violation. Several groups around the world are carrying out the needed calculations. In the case of the EDMs of nuclei, the situation is the same as with the incoherent contribution to $\mu \to e$ conversion: a combination of nuclear effective field theory and lattice QCD would be needed [37].

8.6 Neutron-antineutron oscillations

Calculations of neutron-antineutron oscillations can follow on the success of lattice-QCD calculations of neutral-meson (K, B, and B_s) mixing. The main technical obstacle is that a six-quark operator is needed. In the past year or so, pioneering calculations have begun.

9 Nuclear Energy Applications of Project X Stage 1

Project X Stage 1 will provide capabilities that are unique in the world for carrying out development activities critical for future advanced nuclear power systems. A continuous wave proton beam with approximately 1 MW beam power driving a spallation target produces copious neutrons with an energy spectrum well-suited to that which is encountered in advanced nuclear systems. Project X Stage 1 can serve two primary missions relevance to nuclear power:

- as a driver for a neutron source for nuclear materials and fuels irradiation studies;
- as a test-bed for the development of new reactor concepts, such as those using liquid metal or molten salt coolants, and accelerator-driven subcritical reactor systems

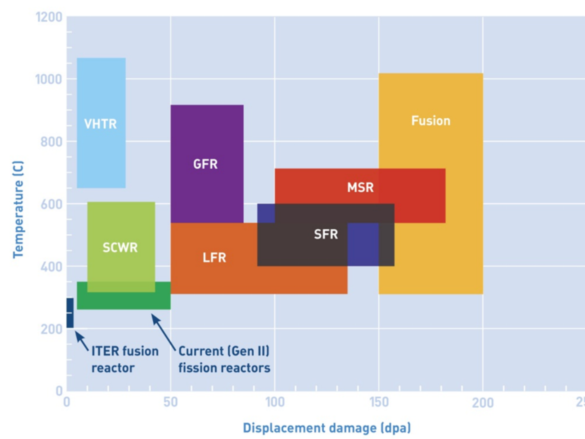

Figure 4: Operating regions in material temperature and displacement damage (measured in lattice displacements per atom) for current fission reactors and future fission and fusion reactors. Fission reactors include very-high-temperature reactors (VHTR), supercritical water-cooled reactors (SCWR), gas-cooled fast reactors (GFR), lead-cooled fast reactors (LFR), sodium-cooled fast reactors (SFR), and molten-salt reactors (MSR). From Ref. [43].

Future advanced nuclear power systems require materials that are capable of withstanding very severe radiation doses. Figure 4 shows the anticipated material temperature and radiation dose, measured in displacements per atom, for a variety of advanced nuclear reactor technologies, compared to today's power reactors. In particular, to develop a practical fusion energy reactor requires materials capable of withstanding doses up to 200 displacements per atom. Materials with radiation tolerance factors of two to ten beyond those available today are required. As a near-term need, materials characterization is required in order to ensure the safety and sustainability of the present reactor fleet in the context of ongoing lifetime extensions of the fleet.

In addition to a materials program, Project X Stage 1 will provide the capability for in-beam experiments aimed at new advanced reactor concepts that use liquid metal or molten salt coolants. It will also provide a test-bed for demonstration of critical technologies for accelerator driven subcritical reactor systems.

A dedicated "Energy Station" utilizing the high power 1 GeV beam delivered to a spallation target can address the following key issues relevant for nuclear energy:

- ensure the sustainability and safety of the current fleet of reactors for current lifetime extensions from 40 to 60 years, as well as future extensions from 60 to 80 years or more;
- develop new higher performance and safer reactor fuels and materials;
- enable the development of innovative economical small reactors;
- enable the development of new advanced reactor concepts, such as those using liquid metal or molten salt coolants;
- enable the development of transmutation fuels for reducing legacy wastes requiring deep geologic storage; and
- enable the investigation of accelerator driven systems as a means for transmutation of waste from power reactors.

The need for a dedicated fast neutron source for materials irradiation is a recognized need that has been under discussion for decades. Project X Stage 1 would provide a unique capability—high power proton beam delivered in a continuous wave format—that ideally suits the needs of the advanced nuclear systems community.

10 Project X Stage 1 Accelerator Configuration and Performance

10.1 Project X Reference Design

In this section, we outline the ideas behind the Project X accelerator, focusing on Stage 1. Project X is the centerpiece of the Fermilab strategy to develop a world-leading Intensity Frontier program and to lay the groundwork for eventual construction of a Neutrino Factory or Muon Collider. Project X is an integral part of the 2011 Fermilab Strategic Plan (*A Plan for Discovery*, `https://www.fnal.gov/directorate/plan_for_discovery/`).

The primary mission elements to be supported by Project X include:

- Long-baseline neutrino experiments: Provide proton beam power greater than 2 MW at any energy between 60 GeV and 120 GeV onto a neutrino production target.
- Rare-process experiments: Provide MW-class, multi-GeV, proton beams supporting multiple precision experiments with kaons, muons, neutrinos, nucleons, and nuclei simultaneous with the long-baseline neutrino program.

- Muon facilities: Provide a path toward a muon source for a possible future Neutrino Factory and/or a Muon Collider.

- Nuclear energy: Provide opportunities for implementing a program of nuclear energy applications, including materials development and Accelerator Driven Systems for waste transmutation and/or energy generation.

A concept for a high intensity proton facility, known as the Project X Reference Design, has been developed to meet the high level design criteria listed above in an innovative and flexible manner. The Reference Design is shown schematically in Fig. 5. The primary elements are:

- An H^- source consisting of an ion source, RFQ, and Medium Energy Beam Transport (MEBT) augmented with a wideband chopper capable of accepting or rejecting bunches in arbitrary patterns at up to 162.5 MHz;

- A 3 GeV superconducting linac operating in continuous wave (CW) mode, and capable of accelerating an average (averaged over $> 1\ \mu s$) beam current of 1 mA, and a peak beam current (averaged over $< 1\ \mu s$) of 5 mA;

- An RF beam splitter that can deliver the 3 GeV beam to multiple (at least three) experimental areas;

- A pulsed superconducting linac capable of accelerating a peak current of 1 mA from 3 to 8 GeV with a 5% duty cycle;

- Modification to the Recycler and Main Injector Ring required to support delivery of 2 MW of beam power from the Main Injector at any energy between 60–120 GeV.

The Reference Design provides a facility that will be unique in the world with unmatched capabilities for the delivery of very high beam power with flexible beam formats to multiple users.

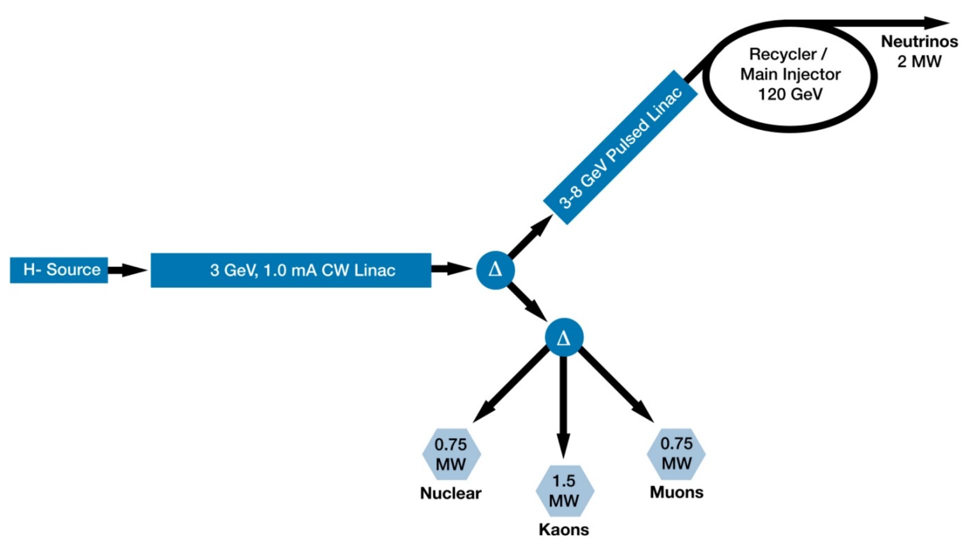

Figure 5: Schematic layout of the Project X Reference Design.

10.2 Staging

Financial and budgetary constraints have led to consideration of a staged approach to Project X, based on application of the following principles:

- Each stage should have a cost significantly below $1B;
- Each stage should present compelling physics opportunities;
- Each stage should utilize existing elements of the Fermilab complex to the extent possible;
- At the completion of the final stage the full vision of a world leading intensity frontier program at Fermilab should be realized.

A three stage approach to the Reference Design consistent with the above principles has been developed. The configuration and performance characteristics of Stage 1 are described below.

10.2.1 Stage 1 Configuration

Stage 1 of Project X comprises a newly constructed 1 GeV superconducting linac injecting directly into the existing Booster. A pulsed linac configuration ($\sim$ 10% duty factor) could provide substantially improved performance within the Main Injector and Mu2e programs, while also providing a platform for the latter stages leading to the Reference Design. Injection into the Booster at 1 GeV is projected to result in a 50% increase in the per pulse proton intensity delivered to the Main Injector complex, relative to current operations. Stage 1 thus establishes the potential for delivering up to 1200 kW onto a long baseline neutrino target (either NuMI or LBNE). Depending upon the operating energy of the Main Injector and the allocation of the Main Injector timeline between neutrino production and a possible rare kaon experiment, significant power could also be devoted to a program based on 8 GeV protons. The balance of available linac beam can be delivered to the Muon Campus currently under development, providing a factor of ten increase in beam power available to the Mu2e experiment. A modest enhancement (10–15% of the Stage 1 cost) of the linac to enable CW operations at 1 mA average current would support newly developed experimental programs devoted to nuclear electric dipole moments (edm), ultra-cold neutrons, and possibly nuclear energy applications.

An additional substantial benefit of Stage 1 is that the existing 400 MeV linac will be retired from service, removing a substantial operational risk within the Fermilab proton complex.

10.2.2 Stage 1 Performance Characteristics

Table 3 summarizes the performance at all available beam energies for Stage 1 of Project X, assuming operations of the linac in CW mode. The organization is as follows:

- The table describes beam performance associated with each particular program supported by Stage 1: Long Baseline Neutrino Program (Main Injector); 8 GeV Program (Booster); 1 GeV Program (CW Linac);
- The table contains two sets of entries, corresponding to operations of the Main Injector at 120 GeV or at 60 GeV;

Table 3: Project X Stage 1 accelerator performance.

Physics program	Long Baseline Neutrino		8 GeV Program		1 GeV Program	
Accelerator	Main Injector		Booster		CW Linac	
MI energy [GeV]	120	60	120	60	120	60
Beam energy [GeV]	120	60	8	8	1	1
Beam power* [kW]	1200	900	42	0	980	980
Protons per pulse	7.5×10^{13}	7.5×10^{13}	6.6×10^{12}	6.6×10^{12}	NA	NA
Protons per second	6.2×10^{13}	9.4×10^{13}	3.3×10^{13}	0	6.2×10^{15}	6.2×10^{15}
Pulse length [μs]	9.5	9.5	1.6	1.6	CW	CW
Bunch [ns]	18.9	18.9	18.9	18.9	programmable	
Bunch length (FWHM) [ns]	2	2	2	2	0.04	0.04
Pulse repetition period [s]	1.2	0.8	0.067	0.067	CW	CW

* Beam power available from the Main Injector and at 8 GeV depend on the disposition of protons provided at 8 GeV and the operational energy of the Main Injector. The table presents a self-consistent set that maximizes beam power to the Main Injector. Not shown in the table is the possibility of diverting some fraction of the time to a rare kaon decay experiment running with a 4.4 s spill over a 10 second cycle. It is assumed here that the disposition of protons will be a program planning decision based on the physics opportunities at the time.

- There is a trade-off (proton economics) between beam power available for the Long Baseline Neutrino and 8 GeV program. The table presents a self-consistent set, based on the maximum beam power achievable in the Long Baseline Program and the corresponding minimum in the 8 GeV program;
- The beam format for the 1 GeV programs is flexible, subject to certain constraints that are described following the table.

Independent bunch structures can be provided from the 1 and 3 GeV linac to three experimental areas simultaneously. The bunch pattern in any particular area must conform to the following requirements:

- Each bunch contains up to 1.9×10^8 H^- ions;
- Bunches in each experimental area must be separated by either 12.4, 24.8, 49.6, or 99.2 ns (*i.e.*, 80, 40, 20, 10 MHz);
- The bunch patterns must repeat every 1.0 μs;
- The total current, summed over the three experimental areas, must be 1 mA averaged over the 1.0 μs period.

An example is given in Fig. 6. The upper drawing shows bunches in the 1 GeV linac, color coded in terms of their ultimate experimental destination. The bottom three drawings show the deconvolution into the structures seen in the three experimental areas. The red area has a 1 MHz macrostructure and a 80 MHz microstructure; the blue area has a 20 MHz beam structure; the green area a 10 MHz beam structure. The number of particles/bunch is 1.6×10^8 and beam power to the three areas is 230, 510, and 260 kW respectively.

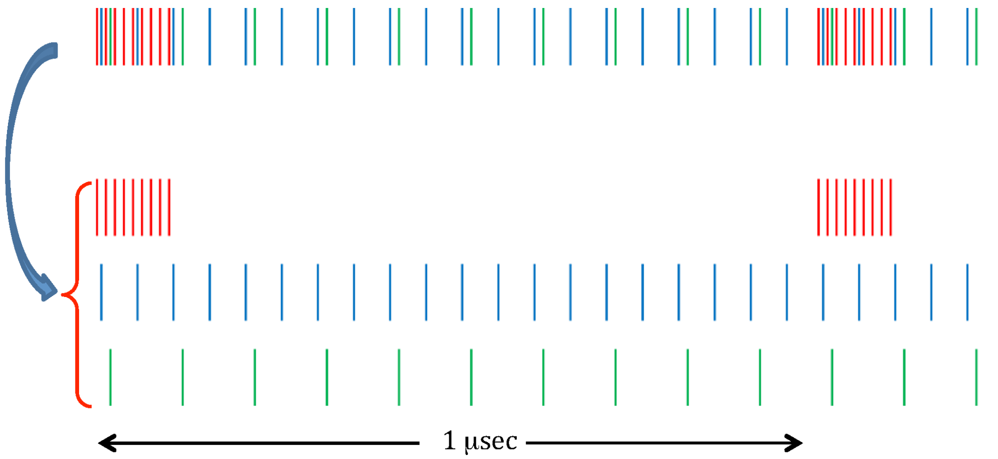

Figure 6: Project X linac loading pattern: Example loading pattern (top line) and its deconvolution into independent bunch patterns delivered to three experiments (red, blue, green) simultaneously. In this example the red experiment received bunches with a 1 MHz macrostructure and a 80 MHz microstructure, while the blue (green) experiment has 20 MHz (10 MHz) pulse structure. For a peak linac current of 4.2 mA the average current is 1 mA, and the red, blue, green experiments receive 700, 1540, and 770 kW respectively.

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