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PNNL-33439

Rapid Acceleration of Outcomes in Physics

Final Report for the Nuclear Physics, Particle Physics, Astrophysics, and Cosmology (NPAC) Umbrella Project

September 2022

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U.S. DEPARTMENT OF ENERGY

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1.0 Introduction

The normal matter in our universe, *i.e.*, things made of atoms, turns out to be only a small fraction of the total matter known to exist. That implies two major questions that are among the most pressing issues in modern science:

1. What is the nature of the more dominant form of “dark” matter that so far we can only infer from its gravitational effects on ordinary matter?
2. How does the universe have any matter in it at all, given that the microscopic laws of physics as currently understood imply it should all have annihilated very shortly after the Big Bang?

The Nuclear Physics, Particle Physics, Astrophysics, and Cosmology (NPAC) Initiative addresses the first question by supporting experiments that would directly detect dark matter when it interacts with very sensitive detectors. There are two leading candidates for dark matter that are plausibly detectable in terrestrial searches: axions and weakly-interacting massive particles, or WIMPs. Early NPAC investments supported PNNL involvement in the Axion Dark Matter eXperiment (ADMX), which has produced the world’s most sensitive axion search to date [1,2]. Work associated with the current generation of the experiment is funded by the DOE Office of High Energy Physics (HEP), while R&D toward future searches for higher mass axions [3] proceeds under NPAC. Likewise, early NPAC support for WIMP searches has graduated to the HEP-supported Super Cold Dark Matter Search (SuperCDMS) experiment. SuperCDMS has produced world-leading limits on potential WIMP candidates [4] as well as a number of other exotic candidates and processes [5,6,7].

The key to answering the second question above is widely believed to involve neutrinos. Unlike any of the other fundamental subatomic particles in Nature, neutrinos could be their own antiparticles leading to processes that violate the symmetry between matter and antimatter. Through a process called leptogenesis, interactions in the early universe would preferably produce matter, leading to the present matter-dominated universe [8]. The only practical way to discover this required neutrino property is to observe the process of neutrinoless double-beta ($0\nu\beta\beta$) decay. Forbidden by the Standard Model of particle physics, $0\nu\beta\beta$ is permitted if neutrinos have mass and are their own antiparticle. Present limits in the half-life for this decay are on order 10^{26} years [9], with a new generation of experiments poised to reach 10^{28} years over the next decade. NPAC has invested heavily in one of the candidates: the Next Enriched Xenon Observatory (nEXO) [10]. Similarly, NPAC has made a priority of determining the absolute mass of the neutrino – the other necessary ingredient – a top investment priority via the Project 8 Experiment.

2.0 The Nuclear Physics, Particle Physics, Astrophysics, and Cosmology (NPAC) Initiative Umbrella Project

The time scales for such ambitious experiments as discussed above span many decades. Although many NPAC investments have graduated to externally supported research, other aspects still require NPAC support to realize their full potential. The project reported here was an umbrella covering research required in the last years of the initiative to ensure long term viability of these new programs. Small projects under the umbrella supported activities including:

1. Focused R&D required to finalize and/or demonstrate capabilities with high probability of graduation to sponsor support in the very near term.
2. Lab work or other research not appropriate for discretionary funds required to support major proposals or community planning exercises.
3. Targeted new opportunities within the science domains of NPAC where the required internal investment and risk is low compared to the reward.

Six subprojects, described in the following subsections, were supported under the umbrella.

2.1 ^{42}Ar Production in Earth's Crust

Argon is a key detector material in rare event searches. Geologically sourced argon (underground argon, or UAr), such as that co-produced in natural gas extraction, is very low in natural radioactivity due to its extended protection from cosmic rays. It has been shown to be heavily depleted in argon-37 and argon-39. A question still remains about how much argon-42 might be contained in UAr. This subproject explored various nuclear reactions that might produce argon-42 underground. Such reactions are found to be rare such that it is safe to expect depletion also of argon-42.

2.2 nEXO Time Projection Chamber (TPC) Design

The search for neutrinoless double-beta decay with the nEXO experiment was a major NPAC investment over its lifetime. This subproject supported the development of construction project plans in preparation for consideration of critical-decision (CD) 1 status at DOE. In particular, it supported elements of the planning that required engineering analysis and decisions. The conceptual design of the TPC was developed into a 3D model to support the overall nEXO experiment integration and collaboration.

2.3 Project 8 Phase III Data Acquisition and Computing Development

Project 8 is an effort to measure the mass of the neutrino by the tritium endpoint method, using the new technique of Cyclotron Radiation Emission Spectroscopy (CRES) [11,12]. The Project 8 Collaboration has created a whitepaper for the Office of Nuclear Physics outlining the R&D required to retire risks to such an experiment. PNNL will have responsibilities for data acquisition and signal processing. This subproject supported development of the proposal and created the basic infrastructure required to satisfy the starting conditions of the R&D proposal. PNNL is responsible for the data acquisition and computing systems for the Project 8 Phase III demonstrators. Under this project staff engineers worked to develop firmware for a new data-acquisition platform and started testing of a new data-management software framework. Staff scientists also began work on a new upgrade to the data-analysis software package. All three of these activities supported the R&D proposal by demonstrating initial capabilities for Phase III.

2.4 NPAC Cryogenic Capability Completion

NPAC supported a liquid-argon-based dark matter experiment called MiniCLEAN as part of its original project suite. In later years, NPAC supported the development of capability to perform research on general liquid cryogen targets at PNNL. This subproject repatriated significant components of MiniCLEAN from SNOLab in Sudbury, Ontario, and incorporated them into the liquid-noble capabilities at PNNL.

2.5 Nuclear Astrophysics

The Office of Nuclear Physics completed construction and began operations of a new flagship facility to support research into nuclear astrophysics: the Facility for Rare Isotope Beams, or FRIB. This subproject supported experts to engage with the FRIB community in the development of research and operations proposals, including several successful proposals for first-year experiment beam time. The successful proposals stemmed from PNNL's involvement in the FRIB Decay Station Collaboration. PNNL staff are members of the collaboration as well as serve on working groups within the collaboration. During the initial facility conditioning at FRIB initial runs for staff were able to participate in one of the first FRIB experiments in June 2022.

To further engage in the nuclear astrophysics community, PNNL staff attended several conferences/workshops to promote their research to the greater community and build collaborations that will serve PNNL's growth in this area of research.

2.6 Helium-6 CRES Analysis

NPAC supported aspects of the development of a technique called Cyclotron Radiation Emission Spectroscopy (CRES), primarily for use in the Project 8 experiment to measure the mass of the neutrino. It has been recognized that the technique is also applicable to experiments searching for physics beyond the Standard Model in precisely measured beta decay spectra. This subproject supported the development of the concept for an experiment based on the decay of helium-6, showing that it can likely avoid major systematic uncertainties of other methods. First results of a prototype experiment are under review for publication at the time of this writing [13].

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