Snowmass 2021 — Letter of Interest: The Exotics and Cosmic Ray Physics Program of NOvA

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The NOvA neutrino experiment has an extensive program of astrophysical and beyond-the-standard-model measurements, including searches for magnetic monopoles, detailed characterization of the cosmic ray flux, a search for neutron-antineutron oscillations, multimessenger astronomy, supernova neutrino detection, and dark matter searches. The physics potential of each analysis continues to rapidly improve with exposure. We describe the potential of the Exotics program assuming a run through 2025, and the impact of further running.

NF Topical Groups:

■ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
□ (NF10) Neutrino detectors

I. INTRODUCTION

The NOvA experiment consists of two segmented plastic and liquid scintillator detectors [1]. The Far Detector (FD) is 14 kt with dimensions 60 m by 15.6 m by 15.6 m and is located on the surface. The Near Detector (ND) is 100 m underground and relatively small, with dimensions 16 m by 4.1 m by 4.1 m and a mass of 300 t. Both run a variety of triggers that enable the program of measurements and searches summarized here [2].

II. MAGNETIC MONOPOLE SEARCH

As a large tracking detector on the Earth's surface, the FD has the unique capability to detect low-mass ($< 10^{10}$ GeV) monopoles that would not reach underground detectors while setting much more stringent flux limits than previous surface detectors. It is also able to record tracks as slow as $\beta \approx 10^{-4}$, setting it apart from many previous monopole experiments.

We separate the monopole search into slow and fast regimes, in which the most distinctive aspect of the signal is the track speed and extreme ionization, respectively [3]. A run that continues through 2025 would give an estimated flux limit of $4 \times 10^{-16}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for monopoles with $3 \times 10^{-4} < \beta < 0.8$, matching or surpassing the MACRO and SLIM flux limits [4, 5] while covering a wider range of monopole masses. Both searches are expected to be background free, and so the flux limits scale linearly with exposure.

III. COSMIC RAY STUDIES

A. Seasonal variation

NOvA has published a study of the seasonal variation of cosmic multi-muons in the ND, which is 100 m underground [6]. It confirmed the MINOS observation that the rate of such events underground is unexpectedly higher in the winter [7]. The origin of this effect is unknown, although plausible explanations have been put forward. NOvA's analysis thus far has covered two annual cycles. Collecting data for as many annual cycles as possible provides benefits both quantitative and qualitative. The quantitative benefit comes from the need for statistics in the high-multiplicity bins, where the effect is strongest. But perhaps more importantly, the two years analyzed so far showed rather different characteristics, with no clear explanation. This is not a question of statistics, but must be related to some unidentified conditions that differ from one year to the next. A run through 2025 provides an additional 8 annual cycles, which may or may not be enough to disentangle the relevant effects. Each additional year will provide valuable information.

A similar study using FD data is underway, with useful data beginning in 2016. As with the ND, the two years examined so far show considerable differences.

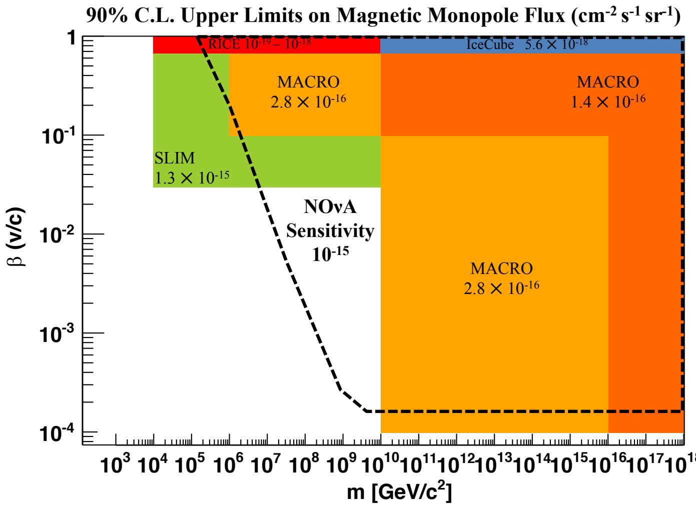

FIG. 1. NOvA's potential monopole limits.

B. Other studies

a. ND: Variation with solar and weather events We plan to use ND cosmic data to examine the influence of short-term weather on the underground muon rate, a known but understudied effect [8]. We also seek to follow up on claims of cosmic ray variability during solar flares [9]. Study of these phenomena rely on sporadic events outside our control, each of which is likely to have different characteristics. Every additional year of running improves the prospects in proportion to the added exposure.

b. FD: E/W effect We are studying NOvA's ability to measure the east/west asymmetry of the low-energy cosmic ray flux caused by the Earth's magnetic field. It is related to low-energy atmospheric neutrinos which form an important background to future proton decay searches. We expect that the data we have collected so far is sufficient to reach a systematics-limited measurement.

c. FD: High energy muons A project has begun to study rare high energy muons in detail using NOvA's fine-grained tracking abilities, testing a spectrum-measuring technique proposed in Ref. [10]. It is not yet possible to say whether this study will be systematics-limited by 2025.

IV. MULTIMESSENGER ASTRONOMY

A. Supernovae

NOvA is the largest carbon-based supernova detector currently operating. In the event of a Galactic supernova, it will provide invaluable data which, in combination with detectors using different target materials, will constrain the flavor content of the supernova burst. The ND and FD have roughly equivalent supernova capabilities, with the ND's small mass being balanced by its low background. NOvA can both selftrigger on a supernova burst, if it is within 7 kpc (13 kpc) for a 9.6 (27) solar mass star [11], and be triggered by alerts from SNEWS [12]. Given the estimated Galactic supernova rate of 3 per century, there is a 15% probability that NOvA observes a supernova burst through 2025, with the probability increasing linearly with each additional year.

B. Gravitational wave coincidence

NOvA triggers on gravitational wave events observed by LIGO/Virgo as part of its multimessenger astronomy program [13]. Our primary observable is a possible flux of supernova-like neutrinos. This could be from an actual supernova, or it could be from an exotic source. We are also sensitive to GeV neutrinos and other similar activity. Gravitational wave astronomy is still a nascent field and there may be surprises in the near future.

A run through 2025 would mean participation in multimessenger astronomy with gravitational waves including LIGO/Virgo/KAGRA's O4 run (2021–2023), planned to be an exposure at least 4 times larger than all gravitational wave observations to date, and a year of the O5 run (beginning 2025), which will monitor a volume of space 10 times larger than before, potentially making available new classes of events and new surprises [14]. As gravitational wave astronomy observatories gain power, each additional year of NOvA running has more potential than the last.

V. NEUTRON-ANTINEUTRON OSCILLATIONS

The NOvA FD is sensitive to the spontaneous conversion of neutrons to anti-neutrons, which would appear as a 2 GeV event with no net momentum. This hypothetical process is suppressed in nuclei, but less so in lighter elements [15], giving about double the event rate per ton in a hydrocarbon detector than in water. NOvA must confront a significant background due to its surface location, but if we can achieve similar background levels as Super-Kamiokande, we will match their current limits [16] with only ~ 2 years of exposure. Our $n\bar{n}$ trigger has been running since 2018. By 2025 we will have collected 7 years of data, with each additional year reducing the limit by between 7% and 14%, depending on the background level.

VI. DARK MATTER SEARCHES

Dark matter may accumulate in the Sun and annihilate, producing GeV neutrinos. The signal is an upwards-going muon in the FD that points back to the Sun. Because of NOvA's low threshold and segmentation, we may be more sensitive than Super-K [17] for dark matter masses 1–4 GeV. The search is likely background-limited by atmospheric neutrinos, so the sensitivity scales as the square root of exposure.

It is also possible to search for dark matter produced in the NuMI beam using the NOvA ND [18]. The signal would be an excess of very forward ~ 10 GeV EM showers. More study is needed to determine whether we are already limited by the systematic uncertainty on the beam flux.

VII. ATMOSPHERIC NEUTRINOS

Atmospheric neutrinos are a background to the $n\bar{n}$ and dark matter searches, but they are also a signal that could be used for an oscillation measurement. As part of these other searches, we have been reading out data-driven triggers configured for sensitivity to atmospheric neutrino events. NOvA's sensitivity has not been estimated, but is not likely to be systematics limited by 2025.

VIII. CONCLUSIONS

The NOvA Exotics program has a wide suite of completed and planned measurements. Many benefit from data collected throughout the full run to 2025 or longer, particularly the background-free search for magnetic monopoles (FD), studies of the variability of the cosmic ray flux (ND+FD), and our multi-messenger neutrino astronomy program with supernovae and gravitational waves (ND+FD), all of which improve linearly with time. The next 5 years of NOvA running will provide unique opportunities to search for new phenomena.

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