Coherent Elastic Neutrino-Nucleus Scattering: Theoretical and experimental impact

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I. INTRODUCTION

Coherent elastic neutrino-nucleus scattering (CEνNS) is a process in which neutrinos scatter on a nucleus which acts as a single particle. Within the Standard Model (SM), CEνNS is fundamentally described by the neutral current interaction of neutrinos and quarks, and due to the nature of SM couplings it is proportional to the neutron number squared [1]. Though the total cross section is large by neutrino standards, CEνNS has long proven difficult to detect, since the deposited energy into the nucleus is $\sim$ keV. In 2017, the COHERENT collaboration announced the detection of CEνNS using a stopped-pion source with a CsI[Na] scintillating crystal detector [2]. This was followed up by the detection of CEνNS with a single-phase liquid argon target [3].

The detection of CEνNS has motivated a flurry of theoretical activity in high-energy physics, inspiring new constraints on beyond the Standard Model (BSM) physics. It has motivated the development of larger scale detectors, and technology to extend current detector sensitivity into lower, sub-keV scale energy regimes. The CEνNS process has important implications for not only high-energy physics, but also astrophysics, nuclear physics, and beyond. This letter-of-intent discusses the scientific impact of CEνNS, highlighting how present experiments such as COHERENT are informing theory, and also how planned experiments that will come online within the next decade will provide a wealth of information across the aforementioned fields of physics.

II. CEνNS SOURCES AND DETECTORS

Given the typical size of a nucleus, the observation of CEνNS requires a source that produces neutrinos with energies less than tens of MeV. There are several terrestrial and astrophysical sources that produce neutrinos at these energies. The three primary terrestrial neutrino sources that are utilized, or will be utilized, for CEνNS are stopped pion/muon sources, nuclear reactors, and ^{51}Cr sources. The three primary astrophysical neutrino sources that may be used for CEνNS are the Sun, supernovae, and the atmosphere. Since all of these sources have distinct neutrino energy spectra and different flavor compositions of produced neutrinos, and in some cases have unique timing signatures, they all provide important and complementary information for CEνNS studies.

To follow up on the COHERENT detection, a diverse set of detector technologies are now under development. The technologies are mature and all are presently used for direct dark-matter detection or other low-threshold experiments. Current detector technologies include systems with CsI[Na] scintillators, P-type point contact (PPC) germanium detectors, liquid argon and xenon detectors, and NaI[Tl] scintillating crystals.

III. NON-STANDARD NEUTRINO INTERACTIONS AND STERILE NEUTRINOS

CEνNS facilitates searches for new physics in the form of non-standard neutrino interactions (NSI) [4, 5]. NSI provide a useful framework to parameterize new physics that couples to neutrinos and can involve either heavy or light mediators. Neutrino oscillation and scattering experiments have been deployed to study NSI, and have placed important bounds on them. However, information on NSI from oscillation experiments is limited since a certain combination of electron, up, and down-type NSI enter the survival and transition probabilities as physical observables.

CEνNS experiments provide an independent handle on a different combination of NSI parameters [6, 7]. The CEνNS cross section is proportional to the weak charge, and in the presence of NSI that allow for neutrino flavor changing processes, the weak charge is modified. This implies a sensitivity to a combination of the up and down vector NSI that is different than that in oscillations. Since different nuclear targets with different neutron numbers may be utilized, multiple detectors comprised of different materials can help to break this up-down degeneracy. NSI models with low mass mediators are particularly interesting for CEνNS [8–10], since they are not within the sensitivity reach of high energy colliders.

CEνNS experiments are also ideally suited to search for sterile neutrinos [11]. In neutrino experiments, sterile neutrinos may either modify the oscillations of SM neutrinos, or they may be directly produced. Direct production exploits the fact that sterile neutrinos inherit a portion of the weak interaction via their mixing with the active neutrinos. This allows for their production in meson decays or neutrino scattering, and typically makes them unstable.

Additional species of neutrinos are predicted in many theories of BSM physics, and their existence has been hinted at by several independent experiments. However, no conclusive theoretical framework has emerged to describe the experimental data. Baselines for ongoing and future CEνNS reactor experiments are $\sim 1 - 20$ m, and in particular for COHERENT the baseline is $\sim 20 - 30$ m for its current operating phase, depending on the specific detector that is deployed. This implies that the L/E for these experiments are similar to that of MiniBooNE [12] and LSND [13], so they provide an independent test of sterile neutrino parameter space.

IV. ASTROPHYSICAL NEUTRINOS

CEνNS has many important connections to astrophysics. CEνNS detectors can directly measure all flavors of the neutrino flux from an astrophysical source. For example, CEνNS can provide a precise normalization and spectral energy distribution of the solar neutrino flux [14]. This measurement will have important implications for understanding the solar metallicity question [15] and for solar neutrino mixing [9, 16]. The detection of CEνNS from a supernova burst or from the diffuse supernova neutrino background (DSNB) will provide the best means to understand supernova energetics [17], and provides an interesting channel to study pre-supernova neutrinos [18]. CEνNS will also provide a new channel to study the low-energy atmospheric neutrino flux, and can specifically help understand how the Earth and the Sun modify the cosmic ray flux at low energies. Combining with DUNE [19], this provides a new method to study CP violation and NSI. CEνNS may also be used to study geo-neutrinos [20].

V. NUCLEAR PHYSICS

In addition to these particle and astrophysics topics, CEνNS is able to provide novel information for nuclear physics, as it provides a direct measurement of the neutron distribution in the nucleus [21], which has not been previously directly measured (except for parity-violating electron scattering). Previous estimates of the nuclear form factor rely to some extent on extrapolation of proton form factor measurements, which have been measured via electromagnetic interactions. The neutron distributions are important input to understanding the equation of state of neutron stars, which are now able to be probed in the era of multi-messenger astronomy. In the SM CEνNS cross section, for both scalar and nuclei with non-zero spin, the dominant contribution to the hadronic current comes from the vector component. Axial-vector contributions to the cross section are subdominant. As we enter into more of a precision phase in CEνNS studies, predictions for the CEνNS cross section at large nuclear recoil energies (tens of keV) will be particularly crucial, especially, since the identification of NSI in CEνNS requires good control over the nuclear and hadronic contributions.

VI. CONNECTION TO DARK MATTER AND AXION LIKE PARTICLE SEARCHES

CEνNS experiments are also naturally suited for more general BSM physics searches, in particular there is a unique complementarity between searches for CEνNS and dark matter. Searches for weakly-interacting massive particle (WIMP) dark matter have progressed rapidly over the past several decades [22, 23]. These searches will ultimately be affected by neutrinos from the Sun, atmosphere, and supernovae which interact in a detector through CEνNS [24]. In particular, a standard spin-independent WIMP with mass ~ 6 GeV induces a signal in an energy regime that overlaps with the solar neutrino signal. Hitting this point of measuring solar and atmospheric neutrinos is an important milestone for future multi-purpose dark matter detectors.

Null results in WIMP searches have stimulated new experiments designed to probe dark matter candidates outside of the canonical WIMP mass range. Experimental searches for low-mass, $\lesssim$ GeV, dark matter are actively underway using a wide range of detector technologies [25]. Stopped-pion based experiments like COHERENT have been shown to be valuable probes of sub-GeV dark matter [26–29]. The large photon flux in these experiments can be utilized to produce dark photons which subsequently decay into dark matter. The timing and recoil energy information reduce SM and experimental backgrounds, making dark matter searches very exciting in these experiments [30, 31].

CEνNS experiments can be used to search for axion-like particles (ALPs) by utilizing their large photon flux. Traditional searches for pseudoscalar ALPs rely on their decay in beam dumps or their conversion into photons in haloscopes and helioscopes. At nuclear reactors and stopped pion experiments, through Primakoff-like or Compton-like channels, the sensitivity to the ALP-photon/electron couplings can improve upon existing limits [32].

VII. SUMMARY

We are just at the very beginning of an exciting era in CEνNS research. There is a multi-faceted experimental effort on-going around the world to expand upon the COHERENT measurements and to study CEνNS using different neutrino sources and detector technology both as a means to study the CEνNS interaction itself and to probe other aspects of physics. Given the broad scientific applications of CEνNS, and its complementarity to many different aspects neutrino physics, it will be an important aspect of the neutrino physics program in the coming decade.

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