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Prospects for exploring new physics with Coherent Elastic Neutrino Nucleus Scattering

Principal Author:
J. Billard
IP2I (Université Lyon 1 and CNRS/IN2P3)
j.billard@ipnl.in2p3.fr

Co-Authors (IN2P3):
CSNSM: Cryogenic detector group
IP2I: MANOIR group
LPSC: Neutrino group

Supporters (non-IN2P3):
Institut Neel: Néel Astrophysics Instrumentation group
JINR: Neutrino and Dark Matter group
MIT: Formaggio's group
Northwestern U.: Figueroa's group
U. of Wisconsin: Palladino's group
UMass Amherst: Hertel's group

Abstract

Thanks to its exceptionally rich science program, Coherent Elastic Neutrino-Nucleus Scattering (CENNS) has led to significant worldwide experimental efforts, over the last decades, with several ongoing and planned dedicated experiments based on a host of techniques. Most of these experiments are, or will be, located at nuclear reactor sites producing low-energy neutrinos (<10 MeV) at the exception of COHERENT which is looking at higher neutrino energies (~30 MeV) emitted from the Spallation Neutron Source (SNS) in Oak Ridge.

Following the first CENNS detection by the COHERENT collaboration, 40 years after its prediction, the community is now focusing on performing a high precision CENNS measurement at the lowest nuclear recoil energies, where signs of new physics may arise. To that end, cryogenic experiments are particularly well suited as they have demonstrated $O(10)$ eV energy thresholds with sufficiently large payloads to observe a sizable neutrino signal near nuclear reactors. Following the anticipated timelines from MINER, NuCLEUS, and Ricochet, a first percentage level precision CENNS measurement, with unprecedented sensitivity to various and yet unexplored exotic physics scenario in the electroweak sector, will be delivered at the horizon of 2024 with kg-scale payloads.

Going beyond such foreseen high precision CENNS measurements will require tremendous efforts dedicated towards the construction of the ultimate CENNS experiment. To reach the targeted permil precision, this ultimate experiment will need a payload of the order of $O(100)$ kg, background levels reduced by 10 to 100 with respect to planned or existing CENNS experiments, and to be exposed to a highly controlled and well understood neutrino source. Such experiment, if well motivated from first high precision CENNS measurements to be delivered in 2024, could be a particularly exciting project for the IN2P3 for the next 10 years, based on its leading position within the Ricochet collaboration.

Introduction

Neutrinos continue to be a source of scientific wonder and discovery in nuclear physics, particle physics, and cosmology. Although much has been learned about the properties of neutrinos, much still pleads for more experimental investigation. What is the scale and structure of neutrino masses? Are neutrinos their own antiparticle? Even a question as simple as whether there are more than three types of neutrinos is the source of serious scientific debate. The answers to these questions are not simply for their own sake; they have significant ramifications as to how we construct our description of the Standard Model (SM) of particle physics and could be the gateway for an entirely new physics paradigm. Over the last decades, various experimental efforts based on a host of techniques and neutrino sources have led to two major conclusions: ***i)*** neutrinos have a mass, and ***ii)*** they have significant mixing with each other. Therefore, starting from almost no knowledge about the neutrino sector twenty years ago, we have built a robust, simple, three-flavor paradigm which successfully describes most of the data. However, despite these major breakthroughs, further experimental investigations based on new experimental techniques and unexplored neutrino processes are still dramatically needed to go beyond the SM which, as we know from precision cosmology and particle physics, has to be extended.

The measurement of Coherent Elastic Neutrino-Nucleus Scattering has been a holy grail in neutrino physics since its prediction almost 40 years ago [1]. This elastic scattering process, inducing sub-keV nuclear recoils, proceeds via the neutral weak current and benefits from a coherent enhancement proportional to the square of the number of nucleons (A^2), suggesting that even a kg-scale tabletop experiment will observe a sizable neutrino signal. This opens the possibility to probe the neutrino sector with orders of magnitude smaller experiments than current and planned kiloton-scale ones with a new approach. The full coherence condition, when the wavelength of the scattering is longer than the size of the nucleus, is guaranteed for nearly all nuclear targets when neutrino energies are below ~10 MeV. Such neutrinos are produced in copious amounts in the Sun, and at nuclear reactors.

The search for physics beyond the Standard Model with CENNS requires to measure with the highest level of precision the low energy range of the induced nuclear recoils, as most of new physics signatures induce energy spectral distortions in the sub-100 eV region. By providing the first percentage-level precision CENNS measurement down to $O(10)$ eV, next generation low-threshold experiments aim at going far beyond simply completing the Standard Model picture by testing various exotic physics scenarios. These include for instance the existence of sterile neutrinos and of new mediators, that could be related to the long lasting Dark Matter (DM) problem, and the possibility of Non Standard Interactions (NSI) that would dramatically affect our understanding of the electroweak sector.

International context and state-of-the-art of CENNS searches

Thanks to its exceptionally rich science program, CENNS has led to significant worldwide experimental efforts, over the last decades, with several ongoing and planned dedicated experiments based on a host of techniques. Most of these experiments are, or will be, located at nuclear reactor sites producing low-energy neutrinos (<10 MeV): CONNIE using Si-based CCDs [2]; TEXONO [3], NuGEN [4], and CONUS [5] using ionization-based Ge semiconductors; and MINER [6], NuCLEUS [7], and Ricochet [8] using cryogenic detectors. Only the COHERENT experiment [9] is looking at higher neutrino energies (~30 MeV) as produced by the Spallation Neutron Source (SNS) in Oak Ridge.

The first CENNS detection

In August 2017, the COHERENT experiment has reported the first CENNS detection at the 6.7-sigma

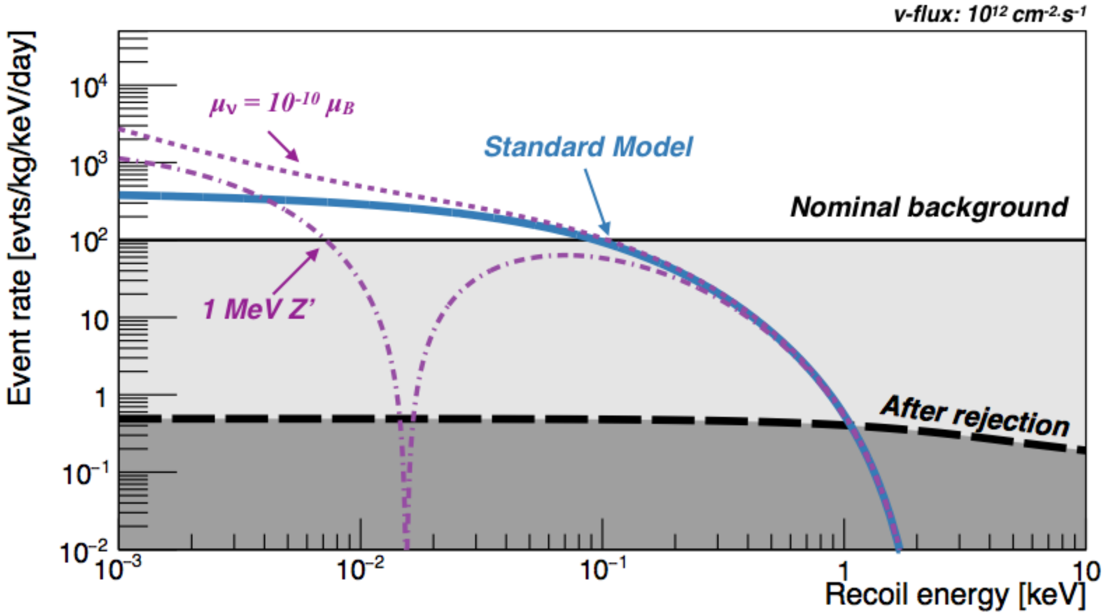

Figure 1: Expected event rate as a function of the recoil energy for the CryoCube detector device from the Ricochet experiment installed within the STEREO casemate at ILL, 8 meters away from the 58 MWth reactor leading to a ~10^{12} $cm^{-2}s^{-1}$ neutrino flux. The blue solid line is the standard model CENNS event rate while the dot-dashed and dashed blue lines are respectively from adding a 1 MeV Z' boson and a NMM of $\mu_\nu = 10^{-10}\ \mu_B$. Eventually, the black solid and long-dashed lines represent the total background before and after discrimination expected in the CryoCube detector. For illustration purposes only, the background rejection capabilities have been extrapolated below 50 eV and considered as independent of energy.

level [9]. This first result was based only on their CsI[Na] detectors cumulating a total target mass of 14.6 kg, with an energy threshold of ~4.25 keV. By using the timing information provided by the pulsed proton-beam, producing pulsed neutrinos, they were able to unambiguously identify a clean sample of 134 ± 22 CENNS events. In addition to their CsI[Na] detectors, the COHERENT collaboration intends to pursue investigating this newly observed neutrino detection mechanism using additional detector technologies such as: ~1-ton LAr detector, a 2-ton NaI[Tl] detector array, and a p-type point contact high-purity germanium detector [9]. About twice the data is now available and an updated result from the COHERENT collaboration is planned to appear by end-2019.

Even though this first detection has only limited sensitivity to new physics, as most new physics signatures will arise in the sub-100 eV region, COHERENT has proven the existence of this new neutrino detection channel that calls for further investigations.

Ongoing and planned CENNS cryogenic experiments

We hereafter focus only on cryogenic detector based experiments as they are uniquely well suited to probe the CENNS process at the lowest energies, i.e. in the $O(10)$ eV energy-range, where new physics signatures are expected to arise (see Figure 1). Indeed, the overwhelming advantage of bolometers, compared to any other detection techniques, is that the deposited energy from a neutrino-nucleus interaction is fully sensed, therefore they act as true calorimeters with no quenching effects. Based on this unique characteristic, new bolometer-based experiments are being developed and will start taking data in the coming years. We give hereafter a brief description only of the future MINER and NuCLEUS experiments as Ricochet will be further detailed in the next section:

MINER is a cryogenic bolometer-based experiment that is located at the 1 MW thermal power research reactor from the Mitchell Institute in Texas. The experiment will use Si and Ge bolometers with a total target mass of 10 kg combined with a projected energy threshold of 200 eV with no background discrimination. The great originality of this project is that the core is movable such that the distance between the core and the detectors can vary from 2 to 10 meters. This is perfectly well suited to study the existence of sterile neutrinos with meter-scale oscillations. Their expected gamma and neutron backgrounds are respectively about 200 and ~1000 event/kg/day/keV below 100 eV, hence about two orders of magnitude above the expected CENNS rate [6]. Their next science run, expected to start in 2020, should pave the way to their future high-precision measurement phase in the coming years.

NuCLEUS is a gram-to-kg scale planned cryogenic bolometer-based experiment that will be deployed at the Chooz power plant, 80 meters away from the two 4.25 GWth reactor cores [10]. It will use a combination of $CaWO_4$ and Al_2O_3 detectors with an assembly of vetoing detectors to provide fiducialization and therefore reject both internal and external backgrounds [7]. The NuCLEUS strategy is to focus primarily on lowering the energy threshold, at the cost of drastically reducing the size of the individual bolometers (~0.5/0.8 g), and is therefore planning to go with two phases of 10 g and 1 kg, that should start in 2022 and 2024 respectively, to reach a high precision measurement. By tuning their heat sensors exclusively to out-of-equilibrium phonons, they have successfully demonstrated an impressive 20 eV energy threshold using a 0.5 g Al_2O_3 detector [11], and are currently commissioning a fully fiducialized NuCLEUS-1g prototype in Munich.

The future Ricochet experiment

Ricochet is a newly formed international collaboration that aims at building the first low-energy CENNS neutrino observatory dedicated to physics beyond the Standard Model. Nowadays, the collaboration counts a total of 9 institutions: four in the USA (MIT, Northwestern U, Wisconsin U., U. Mass. Amherst), the JINR in Dubna (Russia), and four national labs in France from the CNRS (IP2I, CSNSM, LPSC, and Institut Néel (IN)). Since end-2017, Ricochet has been selected as a master project of the IN2P3 and is partly supported by an ERC starting grant dedicated to the development of the CryoCube detector technology and to exploit the CENNS science data from Ricochet.

As of today, the Ricochet collaboration has not yet settled on a final nuclear reactor site but has performed comprehensive studies of two potential sites: ***1)*** the near hall of the Double Chooz experiment located 400 meters away from the two 4.25 GWth cores [8], and ***2)*** the MIT-R with an experimental room few meters away from the 5.5 MWth reactor core [12]. Both sites have neutrino fluxes of roughly ~10^{11} $cm^{-2}s^{-1}$ which, regardless of their anticipated background levels, are too low to fulfill the ambitious Ricochet's scientific goals. Since 2019, the Ricochet collaboration is investigating the possibility to deploy the experiment at the ILL research reactor in using the casemate of the ongoing STEREO experiment after its decommissioning. With a reactor power of 58 MWth, the neutrino flux at 8 m is about $1.2\text{x}10^{12}$ $cm^{-2}s^{-1}$. Interestingly, the ILL reactor is operating in cycles of typically 50 days' duration with reactor-off periods long enough to measure precisely reactor-independent backgrounds. Lastly, the site provides an overburden of 15 m.w.e. against cosmic irradiation and has already demonstrated the successful operation of the STEREO neutrino experiment [13]. In February 2019, the Ricochet collaboration has submitted a Letter of Intent which has been positively reviewed by the ILL scientific committee. Since then, various background characterizations of reactor-correlated backgrounds (gammas and neutrons) combined with dedicated Geant4 Monte-Carlo simulations are ongoing. If the CENNS physics potential of the ILL is confirmed, a proposal will be submitted by early-2020.

The first and unique key feature of the Ricochet program, compared to other planned or ongoing CENNS projects, **is to aim for a single-phased kg-scale experiment with particle identification**, to reject both known and unknown backgrounds, down to the $O(10)$ eV energy threshold. The second key feature is to combine several targets and cryogenic detector techniques to benefit from target complementarity in the quest of new physics searches. To achieve these technological goals, Ricochet is pushing two detector technologies, namely cryogenic Ge- and Si- semiconductors and Zn-superconducting metals, which are uniquely well suited to provide particle identification to discriminate, at the 10^3 level, electromagnetic backgrounds from neutrino induced nuclear recoils at the lowest energies. The collaboration is building two arrays of detectors, that will be mounted in parallel in the Ricochet cryostat:

The CryoCube: is an array of 3 x 3 x 3 = 27 single 30-g Ge and Zn highly performing cryogenic detectors. The crystals will be packed together following a Rubiks cube like topology in a 8 x 8 x 8 cm^3 radio-pure infrared-tight copper box suspended below the mixing chamber with its dedicated cryogenic suspension system [14], and its dedicated front-end electronics [15]. *This development is carried out in collaboration between IP2I, CSNSM, LPSC, and IN, with a CryoCube delivery planned for 2022.*

The Q-Array: is an array of 8 to 16 superconducting 40-g Zn cubes. Each unit will be read out by a transition-edge sensor and the signal feed into a microwave resonant SQUID array, allowing the signals from multiple detectors to be read out by a single feed line. The Q-Array geometry will integrate the CryoCube support structure, allowing for the two technologies to co-inhabit the same cryogenic space and share shielding options. The Q-Array is being developed by the US partners of Ricochet.

Ricochet science reach - 2019 to 2024

Assuming a deployment of Ricochet at the ILL and an energy threshold of 50 eVnr, as already demonstrated with a 33g Ge crystal detector operated at the IP2I [16], a CENNS event rate of ~20 events/day is expected. Following ongoing background characterizations and Geant4 simulations, with an optimized shielding strategy, the anticipated background rate is of about ~100 events/kg/day/keV and ~0.3 events/kg/day/keV before and after discrimination respectively (see Figure 1). Assuming a 20% systematic uncertainties on all backgrounds, Ricochet expects to reach a 5-sigma CENNS detection in a single day, and a 5% precision measurement after only one month of data taking. Such a high precision measurement down to $O(10)$ eV recoil energies, will offer the unique opportunity to study various exotic physics scenarios in the electroweak sector in the coming years [17]:

The Neutrino-Magnetic Moment (NMM): as neutrinos oscillate, they must have a non-vanishing mass and sufficiently large mixing with each other. In the case of a Dirac neutrino, the minimal extension of the standard model leads to a small but nonzero neutrino magnetic moment of about 10^{-19} μ_B (Bohr magneton). This theoretical limit is orders of magnitude below the most stringent ground-based limit from GEMMA $\mu_\nu < 2.9\times10^{-11}$ μ_B (90% C.L.) [18]. However, in some more general extensions, including new physics at the TeV-scale, the NMM can be as high as 10^{-15} μ_B and 10^{-12} μ_B for Dirac and Majorana neutrinos respectively [19]. Therefore, the observation of an anomalously large NMM, inducing sub-100 eV CENNS spectral distortions (see Figure 1), would unambiguously lead to two major conclusions: ***1)*** there is new physics, and ***2)*** neutrinos are Majorana fermions; which will have tremendous implications on the global neutrino physics program. *Ricochet aims at providing the first CENNS-based NMM limit down to $\mu_\nu \sim 10^{-11}$ μ_B (90% C.L.) by 2024.*

Searching for new massive mediators: the Coherent Elastic Neutrino-Nucleus Scattering is done through the exchange of the Standard Model *Z* boson. Plausible extensions of the SM suggest the presence of an additional vector mediator boson [20], that couples both to the neutrinos and the quarks, called *Z'*. The latter could therefore interfere with the standard CENNS process and modify the observed effective weak nuclear hyper-charge. *An improvement by about two orders of magnitude over the current experimental results is expected after one year of data taking with Ricochet.*

Searching for Non Standard Interactions (NSI): new physics that is specific to neutrino-nucleon interaction is currently quite poorly constrained, and is motivated in some beyond-SM scenarios [21]. In the context of a model independent effective field theory, the Lagrangian describing the neutrino-nucleon interaction leads to NSI operators which can either enhance or suppress the CENNS event rate. Strong constraints, as expected from future CENNS experiments, on the neutral current NSI will be mandatory to future long-baseline experiments exploring the neutrino mass hierarchy, such as DUNE [22]. *Thanks to the percentage-level precision anticipated from Ricochet, it is expected to either discover or exclude Non Standard Interactions in the low-energy electroweak sector by 2024.*

Active-to-sterile neutrino oscillations: a precise CENNS measurement will also allow to test the existence of sterile neutrinos. For the typical sterile neutrino masses required to explain the LSND anomaly [23] ($\Delta m^2_{41} \sim 1$ eV) and for typical neutrino energies from nuclear reactor of ~3 MeV the wavelength of active-to-sterile oscillations is of a few meters. Therefore, to be competitive, such a search has to be done few meters away from a compact nuclear reactor in order to observe with sufficient significance the spectra distortions and change in normalizations induced by the existence of a sterile neutrino. *Thanks to its compact reactor core, assuming Ricochet to be deployed at ILL should also lead to competitive sensitivities to eV-scale sterile neutrinos with a new and complementary approach from ongoing experiments.*

Additionally, a precise measurement of CENNS will also have major repercussions in the field of direct dark matter searches as it will lower the so-called neutrino floor which magnitude scales linearly with the CENNS cross section uncertainty [24]. Lastly, future CENNS experiments will also provide the required compact detector technology that will be well suited to perform highly sensitive nuclear reactor monitoring and to study the non-proliferation of nuclear fuels and weapons [25].

Future prospects of CENNS physics - Beyond 2024

The three future cryogenic experiments (MINER, NuCLEUS, and Ricochet) have roughly similar timelines to reach a percentage-level precision measurement of the CENNS process, which should happen at the horizon of 2024. Based on this first set of experiments, if deviations from the Standard

Model predictions are observed, sub-percentage level precision measurements will be mandatory to unambiguously pinpoint the underlying new physics scenario. To that end, two major avenues will have to be investigated: ***1)*** building larger experiments, and ***2)*** lowering the neutrino flux uncertainties:

Building larger experiments, in the 10 to 100 kg-range, will require to readout thousands of bolometers simultaneously. Major technological breakthroughs, especially in the fields of multiplexing and thermal sensor optimizations, will then be required. Additionally, to fully benefit from the larger payload, lower background levels will have to be achieved, hence setting tighter constraints on material selection, on passive/active shielding strategies, and on understanding the low-energy backgrounds that low threshold experiments are now starting to explore. This is particularly challenging as the background levels, planned by next generation cryogenic CENNS experiments, are already at the level of the ones achieved by the best cryogenic dark matter search experiments which are operating underground [26]. It is in this context that the NuCLEUS and Ricochet collaborations have signed together, in July 2019, a consortium agreement in order to share information and knowledge, with the goal to design the ultimate cryogenic CENNS experiment beyond 2024.

With the background levels and the targeted payloads envisioned by the next generation experiments, their achievable precision measurement at nuclear reactors will be limited by the neutrino flux uncertainties, in both shape and normalization. Indeed, the fact that traditional neutrino detectors, based on the Inverse Beta Decay neutrino process, are not sensitive to neutrinos below 1.8 MeV, they are unable to provide any constraints on the low-energy part of the neutrino spectrum that will be probed by future CENNS experiments. Additionally, the overall normalization of the neutrino flux is usually derived from the measurement of the thermal power of the reactor with an accuracy in the few percent level, for both commercial and research reactors. Therefore, probing new physics with sub-percent level precisions will require neutrino sources whose intensities can be measured with much greater accuracy. To that end, it has been recently proposed to use activated 5 MCi ^{51}Cr source whose neutrino spectrum consists of four monochromatic lines, including the most energetic 747 keV (81%) and 752 keV (9%) lines which can be exploited for the measurement of CENNS [27]. Such artificial source has been successfully employed in the past by the GALLEX [28] and SAGE [29] experiments and have demonstrated flux uncertainties, thanks to a dedicated heat monitoring, in the few permil levels. Due to the very low neutrino energies and the potentially high source induced backgrounds, using such neutrino sources will be very challenging but may also be required for the future ultimate generation of CENNS experiments beyond 2024.

Based on its leading role within the Ricochet collaboration, the IN2P3 would be particularly well positioned to lead the design and the construction of this ultimate CENNS experiment combining together: ***1)*** low energy thresholds in the $O(1)$ eV-scale, ***2)*** $O(100)$ kg-scale payloads of multiple target materials, ***3)*** total background levels of the order of $O(0.1)$ evt/kg/day/keV, and ***4)*** be exposed to an accurately known and controlled neutrino source, such as the proposed 5 MCi ^{51}Cr one [27]. Such a project, if well motivated from first high precision CENNS measurements to be delivered in 2024, could be a particularly exciting project for the IN2P3 to investigate for the next 10 years.

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