CEνNS reactor neutrino detection using recoil damage tracks in crystals

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Recently it has been proposed by Baum *et al.* (Phys. Lett. B **803** (2020) 135325) to look for Dark Matter by identifying the damage tracks in crystals caused by nuclear recoil resulting from Dark Matter scattering. Here, we explore the feasibility of using this concept for the detection of reactor neutrinos via the CEvNS reaction since CEvNS, like Dark Matter scattering, leads to nuclear recoils in the keV-range. The obvious advantage of looking for CEvNS from reactor neutrinos is that this a well-known Standard Model reaction and the neutrino flux from a reactor is very high. Moreover, tailor-made materials can be employed. Apart from applications to basic science passive crystal detectors could be attractive for nuclear non-proliferation safeguards acting very much like a smart tag and fitting overall well into accepted IAEA operating procedures. We present an estimation of the track length distribution from CEvNS and compare it to the one of the most pernicious background source, cosmic ray neutrons. We find that even without shielding the CEvNS track number can exceed the neutron background track number by a factor of few for suitably chosen materials and a detection with gram-scale crystals appears possible.

I. INTRODUCTION

Neutrinos are quite interesting and peculiar among elementary particles. They are everywhere around us, with about a 100 trillion of them passing through our bodies every second. They're very light and fast, yet quiet particles, rarely interacting with anything. They come in several flavors, the ones already observed are electron, muon and tau neutrinos. They can oscillate and can even change flavor type without requiring a decay. This is not the only neutrino property that confounds physicists today. Neutrino behavior is so distinct it even points to new physics and holds answers to deep unresolved mysteries like matter-antimatter asymmetry. Yet they're are extremely difficult to detect and understand. So, innovation in detection technology is crucial to bridge the gaps in our knowledge about them.

Neutrinos are produced during weak decays from a wide range of sources. Some of their sources from the perspective of scientific research include supernovae, neutron stars, natural nuclear reactions in the core of a star such as our sun, cosmic ray interactions with atoms, cosmic neutrino background from the Big Bang model, beta decay of atomic nuclei or hadrons. In fact, any accelerated particle beams that strike atoms can produce them. Artificial neutrino sources include nuclear reactions in particle accelerators, nuclear bombs and nuclear reactors. In this project we'll focus on neutrinos produced in a nuclear reactor and discuss their detection using a method that utilizes damage track analysis in crystals, as adapted from research work done by Baum, *et al.* [1].

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II. SCOPE FOR NUCLEAR NON-PROLIFERATION

Reactors are incredibly useful neutrino source because they produce a huge flux of low energy neutrinos, and also because these neutrinos come in only one flavor: electron antineutrinos. This is a big advantage because in particle physics, it's really beneficial for experimental design purposes to know exactly what the target of observation is going to be[2].

Reactor neutrinos are born in a process called beta decay, which happens inside the atomic nucleus. When neutrons induce fission in uranium or plutonium for instance, their atoms break up into lighter elements and these fission fragments undergo beta decay as they become more stable. Some of the energy from this interaction is carried away by neutrinos, which are not radioactive themselves. There are lots of different things scientists can measure from these outgoing neutrino fluxes. Neutrino detectors can be positioned at a range of distances from the reactor. Different distances impart different opportunities for measurements that provide valuable information on how these neutrinos oscillate and change over an interval[2].In our case, our detector would probably be within a short range of $\leq$10m of the reactor.

Detecting reactor neutrinos can not only help scientists understand neutrinos better, but also provide a way to help sustain nuclear peace and order in the world. The backbone of the international effort to prevent the spread of nuclear weapon is the Treaty for the Non-proliferation of Nuclear Weapons (NPT) and the International Atomic Energy Agency (IAEA) is charged with verifying compliance of the 191 member states. Neutrino detectors are sensitive to reactor power and fuel changes and can complement the tools already at the disposal of international agencies to safeguard nuclear facilities and to verify adherence to such agreements, see for instance Ref. [3]. These detectors provide somewhat of a fuel gauge for outgoing reactor flux and can tell us all about reactor status.

In this project, we've investigated and discussed the interactions between CEνNS neutrinos and crystals, and explored the viability of crystals as detectors for this reactor neutrino flux. Crystal detectors for CEνNS events have the potential to be an affordable and powerful tool that can be used for nuclear safeguards. Such verification protocol may prove valuable and serve as a nuclear energy provider's proof of abidance to existing and planned treaties that seek to limit nuclear weapons materials production worldwide [4].

The CEνNS interaction may be detectable using nuclear recoil tracks from these scattering events on crystals which would be optimally designed for this purpose. In the next section, through some theoretical context of CEνNS interaction with crystals, we analyze and discuss some key properties that are are critical when considering the feasibility of such a detection.

III. CEνNS

Coherent elastic neutrino-nucleus scattering (CEνNS) occurs when a neutrino interacts coherently with the total weak nuclear charge, necessarily at low momentum transfer, leaving the ground state nucleus to recoil elastically [5], see Fig. 1. It is the dominant interaction for neutrinos of energy $E_\nu < 100MeV$ [6]. It is important to note that scattering of neutrinos with MeV energies can produce keV scale nuclear recoils.

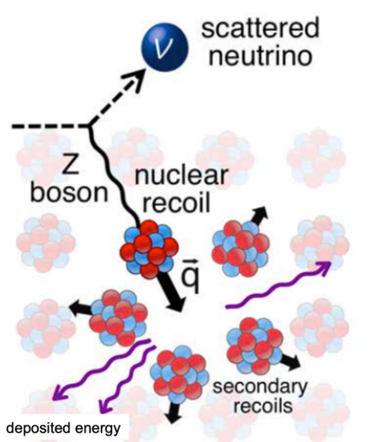

Figure 1. CEνNS event nuclear recoil happens with a Z boson exchange with the target nucleus. In our case, that nucleus would be part of the crystal lattice structure[7]

A CEνNS event observation requires detectors with a low nuclear-recoil-energy threshold in a low-background environment with an intense neutrino flux.

In Ref. [8], CEvNS are talked about as a unique way to study neutrino properties and to search for new physics beyond the Standard Model(SM) of particle physics. Nuclear reactors make possible low energy($\leq$MeV) threshold interactions to deliver large electron anti-neutrino fluxes. Sensitive detectors for low-energy nuclear recoils and high event rate tolerance are much needed for their measurements.

1. *CEνNS event rate estimation*

The CEνNS cross section is enhanced by N^2, with N being the neutron number and thus, can exceed inverse beta decay (IBD) cross section by more than 2 orders of magnitude per unit detector mass. The SM cross section for coherent elastic neutrino scattering is given by [9]

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2}{4\pi} N^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) , \tag{1}$$

where G_F is Fermi constant, M is total mass of the nucleus, T is the nuclear-recoil energy and $E_n u$ is the neutrino energy. Due to low energy of reactor neutrinos we safely can set the nuclear form factor to 1. For a given neutrino energy kinematics limits to the possible recoil energy to be less than

$$T_{\max} = \frac{E_\nu}{1 + \frac{M}{2E_\nu}} \tag{2}$$

The number of interactions is given by

$$n = \frac{G_F^2}{4\pi} M \int_T^{Tmax} \int_0^\infty dE_\nu \cdot \phi(E_\nu) N^2 \left(1 - \frac{MT}{2E_\nu^2}\right) , \tag{3}$$

where $\phi(E_\nu)$ is the reactor neutrino flux which take from a summation calculation performed down to the very lowest energies below inverse beta decay.

2. *Methods for theoretical estimations of track formation*

We follow the formalism described in Ref. [10], to obtain a phenomenological model of track length estimation. In the following, T denotes the target nucleus and V the nuclei in the surrounding crystal. The so-called stopping power, or specific energy loss for a recoiling nucleus T incident on an amorphous target V with atomic number density n_V is given by

$$\left(\frac{dE}{dx}\right)_{TV} = n_V \frac{\pi a_{TV}^2 \gamma_{TV}}{C_{TV}} S(\epsilon_{TV}) , \tag{4}$$

with the reduced energy $_{TV}$ given by

$$\epsilon_{TV} = \frac{\mu_{TV}}{m_T} \frac{a_{TV} E}{\alpha Z_T Z_V}\,, \tag{5}$$

with $Z_{T/V}$ being the number of protons in T/V; α is the fine structure constant.

$$C_{TV} = \frac{\epsilon_{TV}}{E} \tag{6}$$

and

$$\gamma_{TV} = \frac{4\mu_{TV}}{m_V + m_T} \tag{7}$$

where μ_{TV} is the reduced mass of the T–V system, i.e. $\mu_{TV} = m_V m_T/(m_V + m_T)^1$, The screened interatomic Coulomb potential is given by

$$a_{TV} = 0.8853 a_0 \left(\sqrt{Z_T} + \sqrt{Z_V}\right)^{-2/3}\,, \tag{8}$$

with a_0 being the Bohr radius. The reduced stopping power S is parameterized by

$$S(\epsilon) \simeq \frac{1}{2} \frac{\ln(1+\epsilon)}{\epsilon + A\epsilon^B} + k\sqrt{\epsilon}\,, \tag{9}$$

with $A = 0.14120$, $B = 0.42059$ and $k = 0.15$. Now the stopping power in a mix of materials is given by:

$$\frac{dE}{dx_T} = \sum_V \left(\frac{dE}{dx}\right)_{TV} \tag{10}$$

Track length as a function of initial recoil energy is given by:

$$x_T(E_R) = \int_0^{E_n} \left|\frac{dE}{dx_T}\right|^{-1} dE \tag{11}$$

The rate of tracks produces with length x_T per unit target mass is:

$$\frac{dR}{dx_T} = \sum_i^{nuclei} \xi_i \frac{dR_i}{dE_R} \left(\frac{E_R}{dx_T}\right) \tag{12}$$

where index i runs over the different target nuclei which make up the crystal.

We used the equations in this section as the basis of our preliminary estimations of the recoil energies and track lengths for crystals. The original paper that utilizes the aforementioned equations to produce this kind of track length data [6] uses semi-analytic calculations alongside a computational package called Stopping and Range of Ions in Matter, simply known as SRIM. In our case, we used a combination of mathematica and python code framework to generate and plot our dataset.

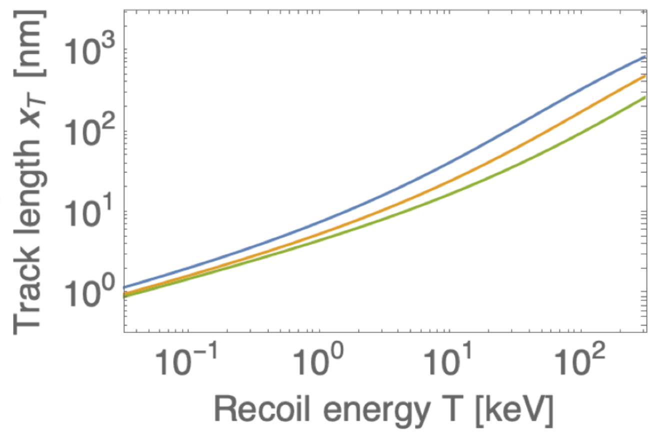

Figure 2. Proportional relationship between track length and energy transfer. Here track length is showcased as a function of recoil energy for the different target nuclei in the geological crystal called Nchwaningite. This proportionality is the reason why tracks are deducible from recoil energies.

To test our model for the connection between recoil energy and track length we produced the plot similar to that showcased in Ref. [10] for the mineral Nchwaningite $[Mn_2^{2+}SiO_3(OH)_2 \cdot (H_2O)]$(See Fig 2).

This theoretical analysis is the key in the method to explore possible crystal properties with the largest CEνNS events cross sections. Crystals can develop damage tracks in their lattices of varying lengths depending on their composition. Once we single out and study the CEvNS tracks in these crystals, we can potentially know a lot of information about the reactor status.We need to research the optimal makeup of such a crystal to maximize precision of measurement of these reactor neutrino fluxes.

The way we study the crystal damage track evolution is by exploiting this crucial relationship between energy transfer and track length. Notice Figure 2: On the x axis, is the nuclear recoil energy from an interaction which is produced at different scales for different incident particles, and on the y-axis is the proportionally increasing damage track length for each of the three elements that make up the crystal. This proportional relationship between recoil energy from CEνNS interactions with target crystal nuclei indicates that based on the type of particle, because this energy range is quantifiable, the damage tracks are quantifiable. This means that CEvNS tracks have the potential to be directly studied using crystals for reactor neutrinos. This detector crystal technology offers a novel, unprecedented, affordable and robust way to detect reactor neutrinos.

[1] Note, that Ref. [10] has a typo here and is missing the $1/(m_V + m_T)$ factor in the definition of γ_{TV}.

IV. DATA ANALYSIS

At first, to explore the feasibility of this detector, it is important to understand qualitatively the raw track event estimations for various candidate crystals. This process is fairly straightforward, relying solely on track events per track length calculations and comparisons to assess favorable composition traits in a detector.This is achieved by generating two plots for a large list of varying crystal compositions. The first plot is a compositional trend analysis, with events per track length for various target nuclei that make up the crystal used, for 2-element and 3-element crystals of varying densities and atomic configurations (See Figure 3 for an example of a 3-element crystal trends analysis). After choosing favorable hypothetical crystal targets from the results of the previous array of plots in different ranges of CEνNS cross sections, we plotted these events per track length alongside events per track length for the largest relevant background source, cosmic ray neutron flux. (See Figure 4 as an example plot)(Also see Figure 2 in [10]).

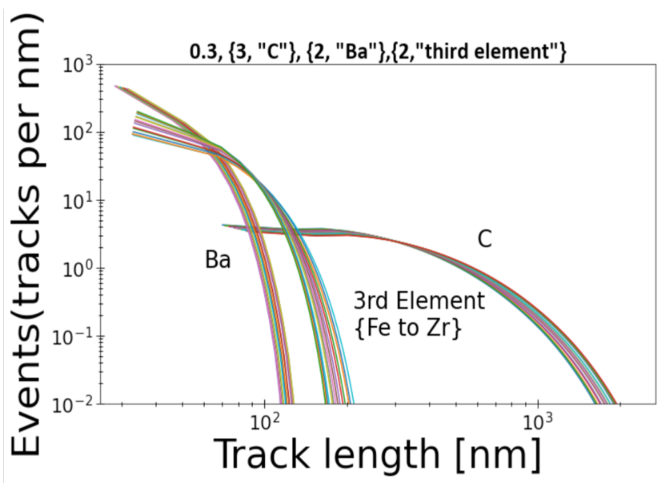

Figure 3. Composition track length trend analysis for crystals with carbon (atomic number = 8), barium (atomic number=56) and a third element (ranging from atomic numbers 26 to 40)

Over the course of a hypothetical crystal analysis of many crystal elemental compositions, densities and atomic configurations, several interesting qualitative results emerged.

Firstly, the crystal damage events per track length do not change too drastically for different atomic configurations of any combination. This trend is apparent in Figure 3, which is a compositional trend analysis for many crystals together. We note here bundles of tracks, after plotting damage track events deduced from recoil energies of each element for each crystal.These

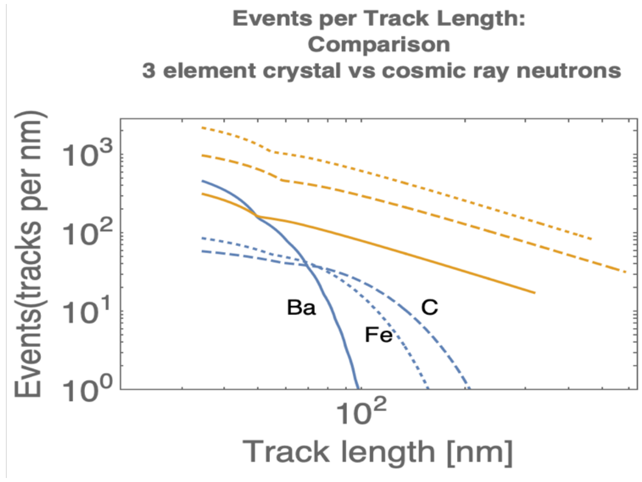

Figure 4. Comparative events per track length analysis for background cosmic ray neutron flux estimations for a crystal composition of C,Ba and Fe. The CEνNS interaction target nuclei tracks are shown in blue. In orange, we see a significant background source, cosmic ray neutrons which also generate tracks on the target nuclei. Each pair made up of crystal element and cosmic neutron flux is shown in different line types.

hypothetical crystals are made of three elements in different ranges of atomic weight. For this example plot in Figure 3, the crystals were all made up of three atoms of carbon, two atoms of barium and two atoms of another third element of an intermediate weight. To analyze multiple plots, keeping the first two elements unchanged, the third element was chosen from elements in the range of atomic numbers 26 to 40. Plotting combinations of many, many hypothetical crystals of varying densities and atomic combinations is crucial in figuring out whether any particular crystal combination may have properties that affect these track lengths differently than others. What we found was that for all hypothetical two-element crystals and three-element crystals of varying compositions analyzed thus far, the crystal damage events per track length qualitatively followed similar trends. Note that the deductions from qualitative plot analyses are preliminary, and only based on a limited set of hypothetical crystal combinations across the periodic table that have been examined.

Secondly, after studying plotted events per track length for CEνNS interactions with various target nuclei using our calculative estimates, we compared the lightest nuclei with the heavy ones. We found that CEνNS events occur at a higher frequency for heavier crystal elements, even though the track lengths for them seem to be shorter. Thus, in general, the heavier elements will tend to have a higher number of events, even if the tracks are short. Inversely, much lighter elements tend to have longer tracks but less events per track length.

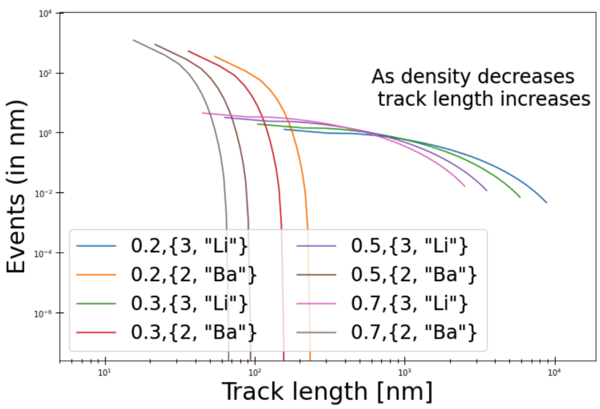

Figure 5. Comparative events per track length analysis for a binary composition crystal of varying densities. Notice that for lower density crystals, the corresponding track lengths are longer.

Thirdly, track lengths for a crystal compound are indirectly proportional to its density. This was apparent after generating the events per track length analyses for a wide range of densities in the same crystals as seen in the example Figure 5. Here, the plot legend shows tracks from four crystals made up of lithium and barium. Each crystal is of a different density, ranging from 0.2 to 0.7. The tracks are longest for the lightest crystals. This process was repeated for multiple crystal compositions for a wider qualitative assessment of the density variation trend.

Lastly, exploring comparable track lengths between background cosmic ray neutrons and our target, the CEVNS interaction, we noticed that the preferred properties in a crystal detector would include a high CEνNS cross section and a lower cosmic ray neutron cross-section. Figure 4, provides an example of this result for barium. The barium CEνNS and cosmic ray neutron cross-sections are represented by the pair of solid lines. In other words, in Figure 4, barium is shown as the solid blue curve and its corresponding cosmic ray neutron tracks are in shown in the solid orange line. They seem to overlap, indicating that here, the CEνNS induced events are similar in number to that of the neutron flux. This particular region in the plot where the CEνNS cross-section exceeds the cosmic ray neutron cross-section indicates that for a certain range of barium tracks in the crystal, there is good potential for CEνNS neutrino detection. This is quite a promising preliminary result, because in a crystal compound where the orange and blue events more or less overlap, or the CEνNS cross section is higher, we could potentially subtract the known number of tracks generated from cosmic ray neutron fluxes from the total, and the leftover tracks on the crystal would be those from CEvNS events.

The crystal properties that we found thus far seem to be consistent over a large range of crystal compositions, and may prove crucially relevant to the final detector design in the future.

V. FUTURE WORK

Once we generate and study cross-section plots for a much wider range of crystal compositions, we can start to qualitatively hone in on the properties which would maximize reactor-neutrino detection and minimize the interference of tracks from significant background sources. Of course, a detector such as this would need to be carefully designed to deal with other considerations as well, such as accounting for crystal tampering possibilities, changing neutrino fluxes affecting track evolution, etc. As the project proceeds towards its next phases after a thorough investigation of favorable properties in the ideal crystal detector composition, the subtler issues that yet remain unaccounted for, such as (but not limited to) the above-mentioned ones, will be investigated. As with any new detection technology, further fine-tuned theoretical modeling is needed for the crystal detector to be optimized for reactors. After understanding the properties we want in a crystal that maximize the likelihood of neutrino observation, collaboration with material science specialists is needed to address the viability of the chemical makeup of the crystal. Once a crystal has been selected and analyzed across an exhaustive list of constraints that favor CEνNS event detection, it would need to be physically manufactured in a way that minimizes any possibilities of acquiring lattice defects prior to its installment near the reactor. Such defects could potentially induce false data signatures overlapping with our CEνNS tracks, so the crystal detector needs to be as clean as possible at the time of installation. Furthermore, after the crystal is ready, careful experimental setup, data collection and calibration would need to be done to assess and fine tune the final device, so as to account for the subtler issues that emerge in that phase of the detector research.

As with all new innovation in detector technology, it takes a long time and a lot of intermediate steps to get from concept to practical use. However, once the CEνNS crystal detector becomes a well-studied and thoroughly optimized device, it could become an unprecedented, powerful and cost-effective tool for nuclear non-proliferation measures. Due to the relative affordability of this detector in comparison to other reactor neutrino detectors, there is great value in this endeavor. Based on the preliminary calculated estimates of the time ranges for significant tracks to develop on the crystal (a section on those calculations was beyond the scope of this paper), it would only take three months of proximity to a reactor core, for an optimally designed crystal detector to be ready for analysis. Multiple detectors periodically installed near the reactor could provide different opportunities for measurements.

Multiple crystal detector placements could also be a way to adapt towards live monitoring of a reactor core, rather than over a typical expected delay in neutrino flux assessment. There may be many innovative ways that are beyond what we've discussed to improve upon reactor non-proliferation/safeguards by adapting from this crystal detection technology.

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