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Observation of coherent neutrino-nucleus elastic scattering at a beta beam

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We study the prospects for observing coherent neutrino-nucleus elastic scattering with a noble liquid detector operated in a low-energy beta beam. We compute the expected signal rates and background contamination from different sources. We conclude that, with a one tonne detector, 1 yr of operation will suffice to observe this reaction with a very high statistical significance.

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I. INTRODUCTION

In the last decades, neutrino physics has had a great impact on particle physics and cosmology [1]. An impressive series of experiments has allowed us to have a deeper understanding of neutrino properties, in particular, about neutrino masses and oscillations [2,3]. Despite this truly outstanding progress, there are still many open questions about the neutrino nature and its interactions. One such example is that of coherent elastic neutral current neutrino-nucleus scattering. This process, which is flavour-blind, has never been observed. However, the idea of having a sharp coherent forward peak for elastic neutrino-nucleus scattering was already developed in connection with the discovery of weak neutral currents [4,5]. In the reaction under discussion, the neutrino scatters elastically from the nucleus (a composite system) and due to the superposition principle, the nucleon wave-function amplitudes (which are in phase) add coherently [6]. The condition of coherence holds for momentum transfers Q smaller than the inverse of the target size, $Q \ll (1/R)$ where R is the radius of the nucleus. The differential cross section for coherent neutrino-nucleus elastic scattering is [7]:

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{Q_w^2}{4}k^2(1+\cos\theta)F(Q^2)^2, \tag{1}$$

where we assume an incident neutrino of energy equal to k that scatters through an angle θ. G_F is the Fermi constant and Q_w the weak charge of a nucleus with N neutrons and Z protons:

$$Q_w = N - (1 - 4\sin^2\theta_W)Z \tag{2}$$

being θ_W the weak mixing angle. $F(Q^2)$ stands for the elastic form factor; it is a function of the momentum transfer squared:

$$Q^2 = 2k^2(1-\cos\theta), \tag{3}$$

In our calculations, the parameterization we use for $F(Q^2)$ is that of Ref. [8].

The condition of coherence is satisfied for neutrinos with energies of $O(10\ \mathrm{MeV})$ and therefore the cross section is directly proportional to the total number of nucleons (A) squared. In this range of energies, the elastic neutrino-nucleus cross section is larger than cross sections for elastic neutrino-electron scattering or inverse beta decay. Despite its larger cross section, the expected signals are very small and therefore very difficult to observe. Note that the maximum recoil energy ($\sim 2k^2/M$ where M is the mass of the nucleus) for a 50 MeV neutrino is few tens of KeV for a typical target (water, scintillator, noble liquids).

In the literature, there are suggestions to look for coherent neutrino-nucleus scattering at several neutrinos sources (Sun, supernovae, reactors, stopped-pion beams, Earth interior and spallation sources) using different detection techniques [7,9–12]. We propose to look for this reaction at a low-energy beta beam [13,14] using a near detector whose active target consists of a noble liquid (either Xenon or Argon). This kind of detectors offer unique detection capabilities in the field of neutrino physics [15] and have demonstrated their ability to detect very low-energy signals in the context of Dark Matter searches [16–18]. The new concept of a spherical TPC, filled with high pressure Xenon, has also been proposed as a device able to detect low-energy neutrinos as those coming from a galactic supernova and, in particular, it will be able to observe coherent neutrino-nucleus scattering [19]. In the following sections, we describe the proposed experimental set-up and the expected signal rates. Likewise, we perform a careful evaluation of all potential background sources affecting this kind of search.

II. EXPERIMENTAL SET-UP

A. Low-energy beta beam

Throughout our calculations, we have assumed a storage ring similar to that used in Ref. [20]. Its total length is $L = 1885$ m with two straight sections of 678 m each. The detector is located at 10 m from the ring. In steady conditions of operation, the mean number of nuclei in the ring is given by $\gamma\tau g$, where γ is the boost factor, τ is the lifetime of the parent nuclei and g is the number of injected nuclei per second. We have assumed that the stored nuclei will be accelerated at $\gamma = 7$ and $\gamma = 14$. The calculations have been performed considering an antineutrino run (coming from the decay of ^{6}He ions) and a neutrino one (where ^{18}Ne ions are stored). Following the discussion in

Ref. [20], we have assumed that $g = 2.7 \times 10^{12}$ ions/s for ^{6}He and $g = 0.5 \times 10^{11}$ ions/s for ^{18}Ne.

B. Noble liquid detector

We have carried out a full simulation of the detector using GEANT4 [21] (see Fig. 1). The active target is a cylinder 50 cm high and 114 cm in diameter that can be filled with a noble liquid (either Argon or Xenon). To reduce the background contamination, rates have been computed considering a fiducial volume of 340 liters (diameter = 104 cm, height = 40 cm). The fiducial mass amounts up to 1 tonne in case the detector is filled with liquid Xenon and 0.475 tonnes in case liquid Argon is used. Our device can detect simultaneously the ionization charge and the scintillation light resulting from the scattering of incoming particles off Xenon or Argon nuclei. This idea was originally proposed to perform high-sensitivity low-background searches for Dark Matter [22]. Light is read by means of PMTs placed at the detector bottom and at the lateral walls (as a reference we have simulated the geometry of PMTs specially designed for low-background applications, see Sec. III B). With this layout, we detect on average more than 50% of the scintillation photons resulting from the interactions that occur inside the fiducial volume. Ionization electrons are drifted to the liquid surface where they are readout by charge amplification devices (i.e., GEM, LEM, Micromegas [23–25]).

The active target is immersed in a water tank, made of stainless steel, serving as an active veto shield against background. The two volumes are optically separated. The tank is a parallelepiped which spreads over 150 cm from the active volume outer surface. PMTs located at the water-tank walls are used to reject particles penetrating from outside (like neutrons) or coming out from the active target. Albeit not contemplated in our simulations, we expect similar results in case other materials are used as the main component of the external veto system.

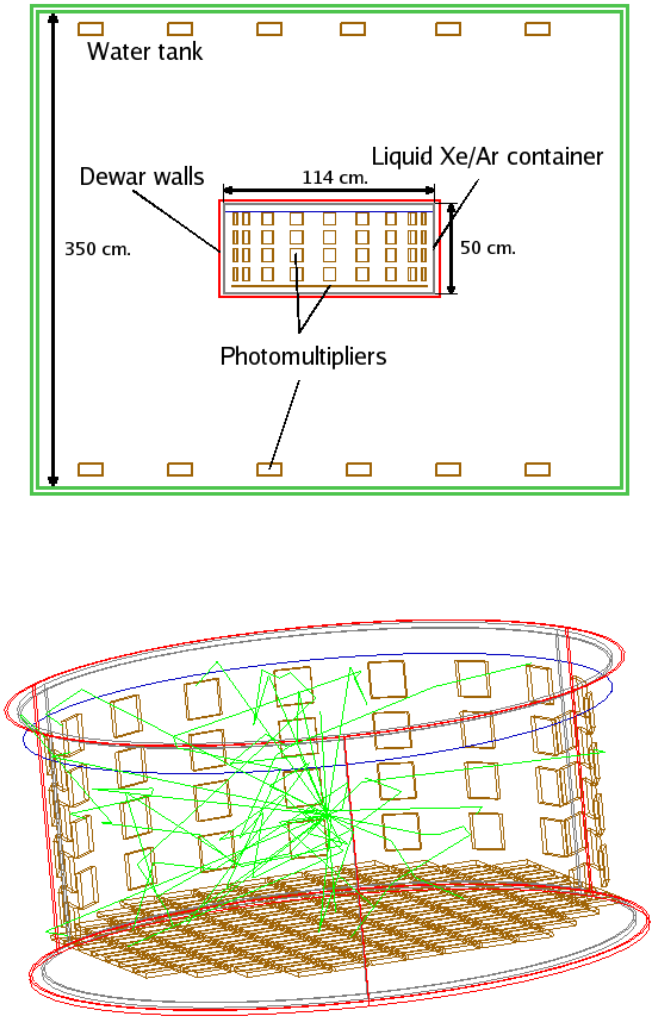

FIG. 1 (color online). (Top) Artist's view of experimental setup (not to scale). (Bottom) GEANT4 simulation of the noble liquid container. Tracks correspond to an interaction occurring in the target. The squares represent the PMT.

III. EVENT RATES AND RESULTS

A. Neutrino signal

The expected number of neutrino interactions (N_{el}) per unit time is:

$$\frac{dN_{\mathrm{el}}}{dt} = N_t \int_0^\infty dk \Phi(k) \sigma(k) \qquad (4)$$

where N_t is the total number of target atoms, $\Phi(k)$ the incoming neutrino flux and $\sigma(k)$ the total cross section (obtained integrating over the solid angle Eq. (1)). To estimate the total neutrino flux, we have to take into account that, given the proximity of the detector to the neutrino source, this cannot be considered as a point source and therefore the calculation is more complex. We compute the flux following the prescriptions given in Ref. [26]. The numerical evaluation of the Fermi function that accounts for the Coulomb modification of the spectrum and which is needed to compute the nuclei decay rate has been taken from Eq. (6) in Ref. [27].

Figures 2 (neutrino run) and 3 (antineutrino run) show, for the two considered targets, the number of expected events above true recoil energy ($E_{\mathrm{rec}} = Q^2/2M$) per tonne per year (we assume 1 y = 107 s). Since the total cross section grows as A^2 (the mass number squared), at low recoil energies Xenon rates are much larger than Argon ones. However as the momentum transfer increases, the form factor for Xenon decreases more rapidly than for Argon, and thus, for higher E_{rec}, we expect larger signal rates in the Argon target. Hence, the most appropriate choice for the target material crucially depends on the expected detection thresholds. We will see in the next section that it will also depend on the level of background contamination coming from radioactive isotopes.

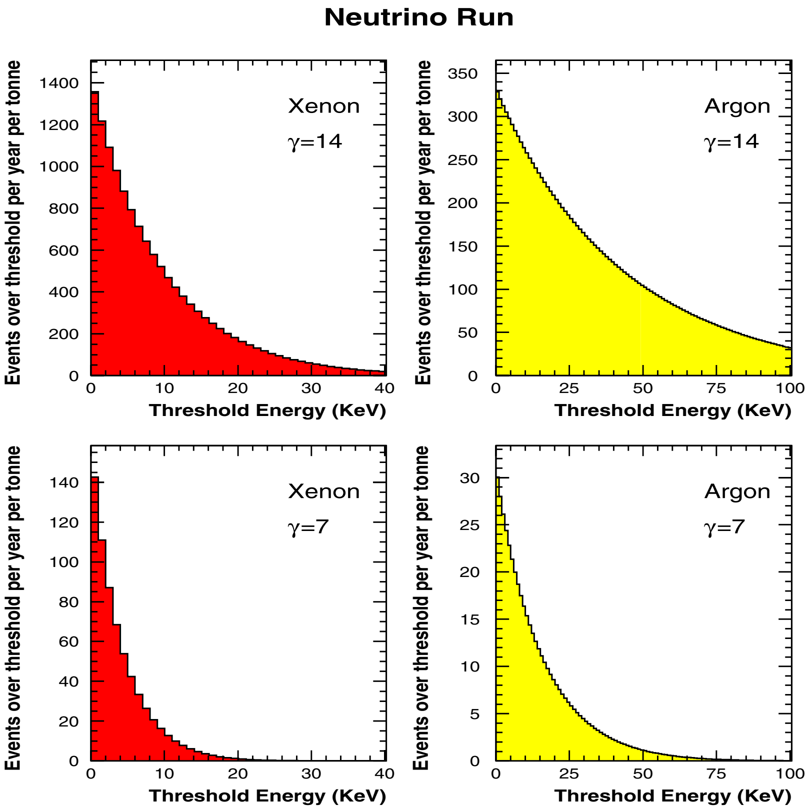
Neutrino Run

FIG. 2 (color online). Number of coherent neutrino-nucleus interactions above true recoil energy threshold per tonne per year for two different boost factors and target materials. Neutrinos come from the decay of ^{18}Ne stored in the ring.

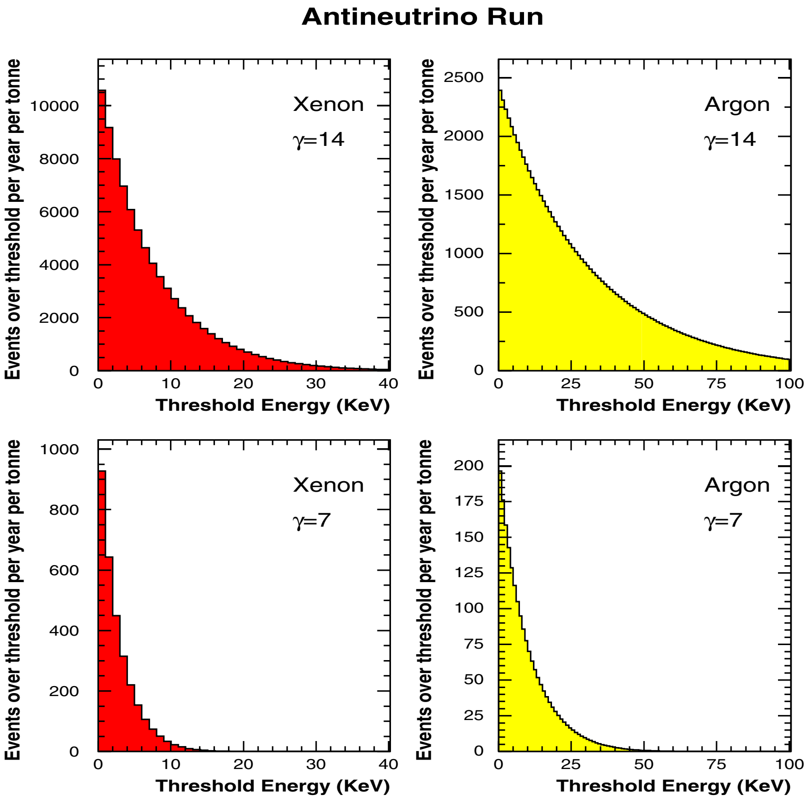
Antineutrino Run

FIG. 3 (color online). Number of coherent neutrino-nucleus interactions above true recoil energy threshold per tonne per year for two different boost factors and target materials. Antineutrinos come from the decay of ^{6}He stored in the ring.

TABLE I. Estimated number of neutrino-nucleus coherent interactions for a low-energy beta beam. Two sorts of ions are boosted at $\gamma = 14$ and $\gamma = 7$ (numbers in parenthesis). We have assumed 1 yr of operation (10^7 s). Rates are given for a detector configuration where the considered fiducial volume (340 liters) is filled either with Xenon (1 tonne of total mass) or Argon (0.47 tonnes of total mass). $E_{\rm rec}$ stands for the true recoil energy.

Running Mode	Target	$E_{\rm rec} > 5$ KeV	$E_{\rm rec} > 10$ KeV	$E_{\rm rec} > 15$ KeV	$E_{\rm rec} > 20$ KeV
Neutrino	Xe	794 (42)	469 (13)	277 (4)	163 (1)
(^{18}Ne decays)	Ar	137 (10)	121 (7)	108 (5)	96 (4)
Antineutrino	Xe	5309 (153)	2717 (22)	1390 (2)	705 (0.1)
(^{6}He decays)	Ar	946 (55)	801 (33)	680 (20)	579 (12)

In Table I, we show, for our simulated detector geometry, the expected number of signal events above a threshold of 5, 10, 15 and 20 KeV in $E_{\rm rec}$. We see the dramatic increase of the rates as a function of the rising γ. For the case where $\gamma = 14$, the expected number of events for both liquid targets is in the range 10^2–10^3. These rates might lead us to think that prospects to discover coherent elastic neutrino-nucleus scattering at a low-energy beta beam with a 1 tonne noble liquid detector are very promising. However before drawing any conclusions, we must carefully evaluate all possible sources of background.

B. Background estimation

Background events are computed for the detector layout described in Sec. II B. In what follows, we cautiously assume that, due to instrumental limitations and in order to guarantee very high detection efficiencies, we cannot detect signals below 15 KeV of true recoil energy. The estimation of the overall background event rate in the fiducial volume must take into account both internal and external sources of gamma rays and neutrons. Among the external ones, we assume that beam-induced background, being mostly composed of low-energy particles, is efficiently reduced by the external water veto. Hence the most important background sources to study are:

(i) *Contamination from radioactive nuclei and Xenon or Argon isotopes.*

For a detector made of Argon, an important source of background comes from the presence of radioactive ^{39}Ar. This is a beta emitter that is produced in interactions among natural atmospheric Argon and cosmic rays. Recent measurements give specific ^{39}Ar activities of about 1 Bq per kg of natural Argon [28], which translates into rates of the order of 0.5 kHz in the case of the proposed detector. It seems that the combination of scintillation light and ionization detection, together with pulse shape discrimination can reduce this kind of background to a tolerable level (see [18,22]). Since this is an issue that is being experimentally settled, we will no longer consider Argon and will focus our interest in a Xenon target.

Among radioactive Xenon isotopes, ^{136}Xe is the most important one. It decays through a double beta decay and therefore, given the small probability of the process, the resulting count rate, in the energy band of interest, is negligible compared to other sources of background, even before any rejection cut is applied.

Krypton and Radon are two radioactive nuclides present in commercially available Xenon gas at the level of tens of ppb. Purities of Kr in Xe well below 1 ppb can be reached by distillation, using charcoal column separation technology as developed by the XENON collaboration [16]. These methods will also effectively remove Radon contamination with gas recirculation and cold traps. The highest contamination comes from ^{85}Kr, which β-decays with an endpoint energy of 678 KeV. With the mentioned purity level, the expected background for the assumed mass and detector rejection power is 150 events/year.

(ii) *Neutrons from detector components.*

Another important source of background can come from neutrons produced by radioactive contamination of the materials constituting the detector itself, mostly from the stainless steel dewar, PMTs and charge readout devices.

Concerning the main dewar, if we assume a total stainless steel (304 L) mass of 1000 kg and a mean contamination of 0.7 ppb of Uranium and Thorium, the predicted residual rate of neutron induced recoils in the inner volume is 500 evts/year [29]. Out of them, only 10% survive the analysis cuts (single recoils with $E_{\rm rec} > 15$ keV).

The use of a copper vessel remains also a valid option. The radioactive impurities can be reduced below 0.02 ppb in some copper samples which would bring the neutron rate to below 1 event per year [29].

If we assume a LEM as the charge readout device, its glass part (Vetronite) is the main source of background. Made of epoxy resin ($\sim 50\%$) and alumino-boro-silicate glass fibres ($\sim 50\%$) the concentration of both, U and Th is about

1000 ppb. For a 1 kg flat LEM disk, this translates into 860 evts/year.

Finally, the background contribution from the photo-tubes must be evaluated. We noticed that the main manufacturers continue to optimize the choice of materials used in the PMTs construction to reduce their radioactivity levels. Typical contamination values for U and Th range from a few tens to several hundreds parts per billion per kg. Among the wide variety of tubes available in the market, it is possible to find out some models specially designed for low-background applications like the 2-inch ETL type 9266. According to Ref. [30], the measured Uranium and Thorium concentrations in Quartz and metal components for this model is as low as 8 ppb. The photo-tubes windows could be coated with Tetra-Phenyl-Butadiene (TPB) to shift the VUV light from Xenon (peak emission at 174 nm) to the maximum of the photo-tube spectral response without an increase in contamination. In order to cover the desired surface with this PMT model, the detector should be equipped with a total of 417 units. The total GEANT4 estimated number of single recoils in the interesting energy range amounts to 120 evts/year.

(iii) *Neutrons from surrounding rock.*

Neutrons coming from the rock can have two origins: (i) those produced underground by cosmic muons (called hereafter "muon-induced neutrons") and (ii) neutrons induced by spontaneous fission and $\alpha - n$ reactions due to Uranium and Thorium present in the rock (called generically "radioactive"). The latter have a very soft spectrum [31] (typically energies of few MeV) and according to our simulations the water veto efficiently reduces this type of background to a negligible level.

The energy spectrum from muon-induced neutrons is harder. They can come from larger distances and produce recoils with energies well above threshold [29]. The active external water veto will efficiently tag crossing muons by Cherenkov light detection. Neutron signals occurring in the fiducial volume in coincidence with water PMT signals will be rejected. More dangerous are neutrons produced by muon-induced spallation reactions in the walls of the experimental hall. We have observed that by asking a single elastic interaction inside the fiducial volume with energy deposition in excess of 15 KeV and no activity detected in the veto, only neutrons about 100 MeV constitute a background. Assuming the experiment will be located at shallow depth (50 to 100 m of standard rock), we have considered a total flux of 50 muons per m^2 per second [32]. This translates into a total muon-induced neutron background of 130 evts/year.

TABLE II. Xenon target: Estimated number of background events from different sources.

Background source	Events/year
Xenon	150
Surrounding rock	130
Internal detector components	1030
Total	1310
Total (including beam pulsed structure)	5

The total estimated number of background events amounts to 1310 per year (see Table II). Let us note that, in real experimental conditions, this steady-state background can be accurately predicted with data taken in periods where the ion beam is off. The final estimation of the background should include the fact that the beam has a pulsed structure (neutrinos show the time stamp of the circulating ions). Assuming that the ion bunches are 5.2 ns (^{6}He) and 4.5 ns (^{18}Ne) long and that there are 20 bunches (within 2 μs) recirculating every 23.35 μs, the duty factor of the decay ring is 4.5×10^{-3} (for ^{6}He) and 3.9×10^{-3} (for ^{18}Ne) [33]. Taking into account this additional rejection factor, the final background rate is ~5 evts/year for true recoil energies in excess of 15 KeV. For this energy interval, the expected number of neutrino events in the case of a Xenon target is 1390 (277) for a antineutrino (neutrino) run where ions are accelerated up to $\gamma = 14$. Such a significant statistical excess would allow, not only to observe coherent neutrino-nucleus elastic scattering, but to carry out an important Physics programme to constrain nonstandard neutrino interactions (see [12] and references therein) or to measure intrinsic electromagnetic properties of the neutrino like its effective charge radius (NECR) [34]. The NECR produces a shift in the value of the effective weak mixing angle of approximately 5%. Assuming that the flux composition is known at 2% [35] and backgrounds can be precisely measured in beam-off conditions and therefore contribute to less than 1% to the total error, we estimate that, for an energy threshold of 15 KeV, after three or four years of data taking in the antineutrino mode (statistical error ~1%) we will be able to observe the effects due to this intrinsic electromagnetic property of the neutrino.

IV. CONCLUSIONS

We have explored the possibility to use a tonne-size noble liquid detector to observe coherent neutrino-nucleus elastic scattering at a low-energy beta beam. We have computed signal rates and have performed a careful evaluation of potential background sources. Our calculations show that the expected background is much smaller than the neutrino signal. The proposed experimental set-up has the unquestionable potential to detect this reaction and offers a high-statistics environment to continue the study of neutrino properties and its interactions.

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