

Search for sterile neutrinos at radioactive ion beam facilities

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Abstract. We propose applications of Radioactive Ion Beam facilities to investigate physics beyond the Standard Model. In particular, we focus upon the search for sterile neutrinos by means of a low energy beta-beam with a Lorentz boost factor of 1. In the considered setup, collected ⁸Li radioactive ions are sent inside a 4 π detector filled with a liquid scintillator, with inverse-beta decay as neutrino detection channel. We provide exclusion curves for the sterile neutrino mixing parameters, based upon the 3+1 formalism, depending upon the achievable ion intensity. The proposed experiment represents a possible alternative to clarify the current anomalies observed in neutrino experiments.

1. Introduction

Open questions concerning fundamental neutrino properties include the neutrino mass scale, the neutrino mass hierarchy, the Majorana versus Dirac nature of neutrinos, and the possible existence of sterile neutrinos. While neutrino oscillations are nowadays an established fact, several anomalies have recently been observed, that cannot be explained within the standard three active neutrino framework. First the MiniBooNE anti-neutrino and neutrino oscillation results are not fully understood, while an increased statistics should help to elucidate the low energy excess and the oscillation hypothesis [1]. This experiment was designed to confirm/rule out LSND, which found an indication for neutrino oscillations at a Δm^2 of about 1 eV² both in the antineutrino channel, using decay-at-rest muons[2], and the neutrino channel, based upon decay-in-flight pions [3]. The second anomaly is known as the reactor “anomaly” [4]. Indeed a recent reevaluation of the electron anti-neutrino flux from reactors has shown a shift in the flux renormalization by 3% [5], compared to the previous predictions. The reanalysis of the reactor experiments, using this new flux, has shown a significant inconsistency with the three neutrino oscillation hypothesis. Finally, some years ago, the GALLEX and SAGE experiments pointed out an anomaly in the neutrino flux measured by putting an intense static ³⁷Ar and ⁵¹Cr sources inside their detectors. This is referred to as the Gallium anomaly. Ref.[6] has performed a detailed analysis including the 5-10% uncertainty on the corresponding neutrino-nucleus cross sections, showing that the Gallium anomaly statistical significance is at the level of 3 σ .



Currently the ensemble of the accelerator, reactor and Gallium anomalies are the object of debate and have triggered an intense investigation. The possible interpretations exploit for example one or more sterile neutrinos, such as in [7], a combination of sterile neutrinos with non-standard interactions like in Ref. [8], while none of the proposed explanations so far provides a comprehensive understanding of all the data and is clear that independent and aimed experiments are necessary to clarify the present situation.

Ref. [9] has proposed the idea of establishing a low energy beta-beam ¹ facility, to dispose of neutrino beams in the 100 MeV energy range, based upon the beta decay of radioactive ions, with $\gamma \approx 1$ (γ being the Lorentz factor) or with an ion boost γ of typically 2 to 7. In the first case, the neutrino fluxes are those of ions that decay-at-rest; while, in the second case, beams of variable average energy are obtained through a boost of the ions. The advantage of having such a facility is to dispose of pure (in flavor) and well known electron neutrino (or anti-neutrino) fluxes. For the physical applications see the review [10]. Most of these applications are based on stored boosted ions. In Ref. [11] we have considered the configuration with $\gamma \approx 1$, with radioactive ions sent to a target inside a 4π detector for the search of the neutrino magnetic moment. Note that Ref. [12] has taken the same configuration for a sterile neutrino search.

In this paper we consider a low energy beta-beam with $\gamma \approx 1$. We consider that the ions are injected into a target inside a 4π detector. The purpose is to use the resulting very low energy neutrino flux to search for new physics. We focus on the search for one sterile neutrino in a 3+1-neutrino flavor framework and present exclusion plots for the sterile neutrino mixing parameters.

2. Possible setups and corresponding neutrino fluxes

Radioactive ion beam facilities produce intense radioactive ions decaying through beta-decay, or electron capture. Since specific radioactive ions can be selected, a pure electron (anti)neutrino flux can be obtained. As first proposed in [9], there exists two alternative ways to produce low energy neutrinos (Figure 1). In the first scenario the decaying ions are stored inside a storage ring, while the emitted (anti)neutrinos are detected in a detector located close to the storage ring. If the stored ions are boosted, the corresponding neutrino spectra have variable energy with the average energy given by $\langle E_\nu \rangle \approx \gamma Q/2$, with Q being the Q -value of the beta-decaying nucleus. Depending on the application envisaged, the neutrino fluxes can be tuned by appropriately choosing the Lorentz boost and a high/low Q -value ion. In the case the ions are not boosted ($\gamma \approx 1$), storing the ions in a small storage ring is a possibility as well. An example is furnished by the storage ring facility currently proposed at HIE-ISOLDE at CERN [16]. While for this specific storage ring the number of stored ions is limited, one can imagine the establishment of a small ring at one of the future intense radioactive ion beam facilities, such as European EURISOL [17], or the US Facility for Rare Isotope Beams (FRIB).

The second scenario to produce low energy neutrinos, consists in injecting the ions into a target placed inside the detector. It turns out that, as long as radioactive ions are slow (i.e. not accelerated to Lorentz boost values above 1), such a scenario is much more efficient than the storage ring case. This is due to a geometrical effect since, only part of the produced (anti)neutrino flux - and not the total flux - traverses the detector if the ions are stored in a storage ring. The average neutrino flux at the detector is further reduced, compared to the injection inside the detector case, if the detector cannot be located very close to the storage ring due to the background shieldings and other necessary instrumentation.

¹ The beta-beam concept was first proposed by Zucchelli to establish a facility for the search of leptonic CP violation [13]. For a discussion on the status of the feasibility of beta-beam facilities see e.g. [14]. Note that Ref. [15] has proposed a method to reach high Q -value ion intensities e.g. for ^8B and ^8Li , which is currently being investigated.

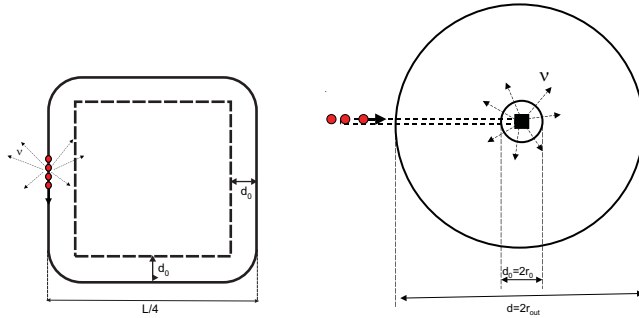


Figure 1. Two possible scenarios to produce low energy neutrinos from radioactive ions at Lorentz boost of 1. Left figure: The radioactive ions decay while circulating in a storage ring. The neutrino detector is installed close to the ring. Right figure: The radioactive ions are injected into a cavity inside a spherical detector.

We consider that radioactive ions are produced and injected into a target with an intensity I of ions per second. This target is installed inside a cavity located at the center of a spherical detector.

3. A 3+1 sterile neutrino oscillation experiment

In the present work we consider a sterile neutrino search within the 3+1 framework with three active neutrinos and one additional sterile neutrino. Besides the usual parameters of the Maki-Nakagawa-Sakata-Pontecorvo matrix, in this case the oscillation formula depends upon the neutrino mixing angle θ_{new} and Δm_{new}^2 , considered to be much larger than $\Delta m_{31}^2 \simeq 2.4 \cdot 10^{-3} \text{ eV}^2$. Implementing more complex scenarios with extra neutrinos is straightforward. The electron neutrino survival probability for $P_{ee}(E_\nu, r)$ is given by Ref. [18]

$$P_{ee}(E_\nu, r) = 1 - \cos^4 \theta_{new} \sin^2 (2\theta_{13}) \sin^2 \left(\frac{\Delta m_{31}^2 r}{4E_\nu} \right) - \sin^2 (2\theta_{new}) \sin^2 \left(\frac{\Delta m_{new}^2 r}{4E_\nu} \right) \quad (1)$$

where a baseline of $L < 2 \text{ km}$ and neutrino energies $E_\nu > 2 \text{ MeV}$ are assumed.

4. Numerical results

To produce low energy neutrinos both β^+ and β^- decaying ions can be considered as electron neutrino and anti-neutrino emitters respectively.² The choice of the ions depends on the achievable intensities, the half-lives and Q -values. Obviously the half-lives should lie in an appropriate range between short and long to make experiments feasible, so that typically half-lives in the 1 s range seem to be a good choice. On the other hand, high Q -values help increasing the total number of events as well as improving the signal-to-background ratio.

Table 1 shows the candidate ions that we have been considering here, as typical examples. As far as ^8Li is concerned, it decays mainly into a broad ^8Be $J^\pi = 2^+$ excited state, at 3.03 MeV, therefore having Q -value centered at 13.1 MeV. Nevertheless, due to the broadness of the final state, the neutrino spectrum is extended well above the energy associated to the centered Q -value. To evaluate qualitatively this effect, we present results for two decay modes³: i) 100% branching ratio to the ^8Be ground state; ii) 100% branching ratio to a narrow excited state at 3.03 MeV. In a real experiment the actual results will fall in-between these two “extreme” cases.

For the ion intensity, we assume 10^{13} ions per second. Instead of taking this parameter as a tunable number (as sometimes done in the literature), here we consider values, that can in

² Note that electron-capture neutrino beams have been considered in [19].

³ Note that an accurate neutrino spectrum might be obtained by considering the ^8Be final state continuum, taking into account the delayed- α spectrum [20].

Table 1. Beta-decay properties of the ions considered in our proposal: τ is the decay lifetime, $E_\nu^{\max}$ is the end-point energy.

Ion	Decay	Daughter (State)	$\tau(\text{ms})$	$E_\nu^{\max}(\text{MeV})$
${}^6_2\text{He}$	β^-	${}^6_3\text{Li} (1^+, 0)$	806.7	3.5078
${}^8_3\text{Li}$	β^-	${}^8_4\text{Be} (2^+, 0)$	838	13.103
${}^8_3\text{Li}$	β^-	${}^8_4\text{Be} (0^+, 0)$	838	16.003

principle be achievable at next generation radioactive ion beam facilities. The predictions we present are obtained by taking 1 year = 10^7 s and a 100% efficiency of the detectors.

We shall consider two types of β^- decaying ions (Table 1). First, because of its very well known aspects relating to its production and management, it is worth taking a look at the physics reach of a facility based on ${}^6\text{He}$. Its low Q -value yields fewer number of counts and, as we will show, this hinders the potential of a setup exploiting this ion, instead of one based upon a high Q -value ion choice. Our proposal for the search of sterile neutrinos is mainly based on the properties of ${}^8\text{Li}$, for which we assume two extreme cases, as mention above, indicated as ${}^8\text{Li}$ -16MeV and ${}^8\text{Li}$ -13MeV ‘ions’.

Our choice of main setup has been dictated by an analysis of the performance of the two possible configurations shown in Figure 1. In both cases, the considered detector is filled in with a liquid scintillator⁴. The electron anti-neutrino detection channel is inverse beta-decay $\bar{\nu}_e + p \rightarrow n + e^+$. A good signal-to-background ratio can be obtained by the addition of Gadolinium and the subsequent detection of the 8 MeV prompt gamma-rays produced by the neutron capture.

We have chosen to present the results of our simulations by means of exclusion plots. The plots show the oscillation parameter space region where our setup is expected to be sensitive to the detection of active-sterile neutrino oscillations. In all our calculations the considered running time of the experiment is of 5 years. Unless contrarily stated, we fix the systematic error to $\pi = 1\%$ in all the analysis presented hereafter; while we will show how our main results change if a larger systematic error is considered. We shall compare the sterile neutrino oscillation parameter regions that can be covered with our experimental setup, to the allowed regions presented in the analysis of Ref. [4], based on reactor neutrino experimental data cumulated so far.

Figure 2 presents exclusion plots calculated from a statistical analysis of the data using total rates. The facility is based on ${}^8\text{Li}$ -13 MeV decaying ions. The aim of the figure is to compare the results obtained for the two experimental setups of Figure 1. Note that for the specific case of the storage ring only, we assume an intensity of 10^{11} ions/s, having in mind a facility like HIE-ISOLDE (although the stored ion intensity is expected to be smaller [16]). Such an intensity should be attainable in a storage ring nearby the EURISOL facility [17]. For the setup geometry, following the TSR proposal for HIE-ISOLDE, we take a square storage ring with straight sections of 61.6 m length and a 1 kton cubic⁵ detector at the storage ring center. (Such a geometry leaves 3 meters space between the detector and the storage ring straight sections [21, 22].) Note that, the number of expected events and, thus the exclusion plots, strongly depends on the setup geometry. For a large detector, as considered here, placing it in the center of the storage ring represents the optimal scenario (if such a detector is located along one storage ring straight section, the event number is reduced by almost a factor of 4). As expected,

⁴ We take as an example $\text{C}_{16}\text{H}_{18}$ with a density of $\rho = 988 \text{ kg/m}^3$.

⁵ The detector base has a size of 9.4×9.4 m and the height is of 11.3 m. Half of the detector is located below the storage ring, and half above.

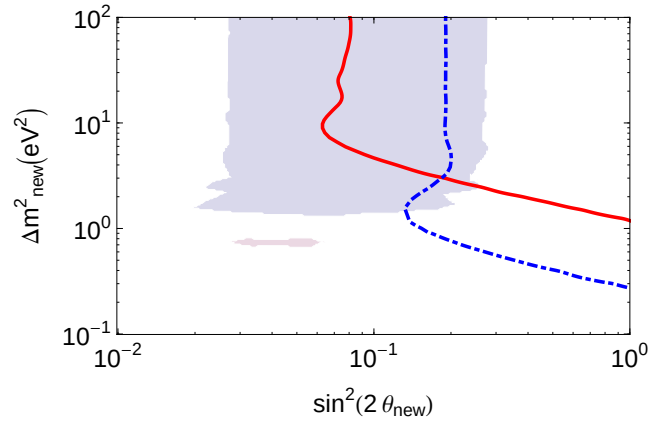


Figure 2. Exclusion plots for the sterile neutrino mixing parameters from an analysis of the data including only total rates. The results are obtained by considering a 3+1 neutrino oscillation formalism. The contours shown are for a C.L. of 99% (2 d.o.f.). The two setups are those of Figure 1. The solid (red) line corresponds to the 4π detector surrounding the source; while the dashed-dotted (blue) line corresponds to the detector place at the center of the square storage ring. The ion intensities are of 10^{11} ions/s for the storage ring and of 10^{13} ions/s for the spherical detector (see text). The source is ^8Li ions decaying mainly to the first excited state of the daughter nucleus (maximal neutrino energy 13 MeV). In both cases a 5 years running time is assumed. For comparison the shaded region represents the 99% C.L. inclusion domain, given by the combination of reactor neutrino experiments and other sources (adapted from Fig. 8 of Ref. [4]).

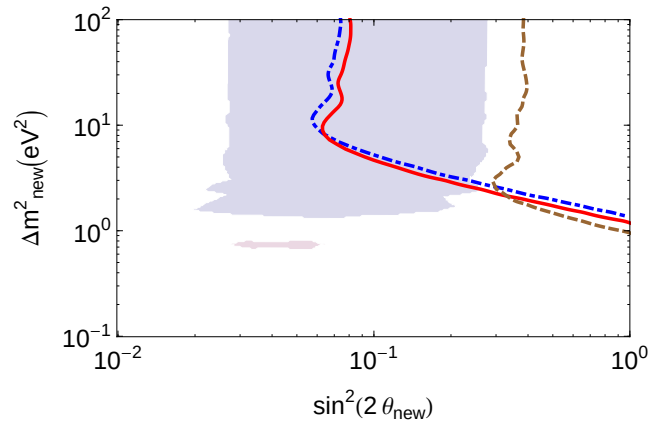


Figure 3. The same as the previous figure (spherical detector only) but choosing different ions: a source of ^8Li ions decaying mainly to the first excited state of the daughter nucleus (solid red line), ^8Li ions decaying mainly to the ground state of the daughter nucleus (dashed-dotted blue line), or a source of ^6He ions (dashed brown line).

although the detector is of 20 tons only, the performance obtained by sending the ions inside a 4π detector is superior to the storage ring one⁶ with respect to the coverage of the shaded region identified by the reactor anomaly. On the other hand, the storage ring setup has a better sensitivity to small Δm^2 .

⁶ Note that this is also due to the higher ion intensity.

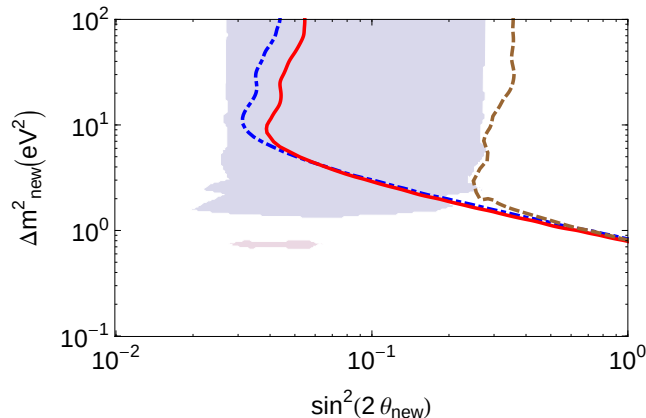


Figure 4. The same as the previous figure but including spectral information, i.e. a binned analysis of the simulated data.

In addition to the aforementioned geometric advantages, the spherical detector setup benefits from the fact that neutrino source is very close to the active detector material (we remind that the radius cavity is of 20 cm only). From now on, all the results we present will correspond to the spherical detector setup.

Figures 3 and 4 show exclusion plots constructed from total rates, and from a spectral (binned) analysis of the simulated data, respectively. Results for three ion sources are shown: the ^8Li -16 MeV, the ^8Li -13 MeV and ^6He cases. The low Q -value of the helium ions clearly hinders the sensitivity of this setup, making it clearly inferior to the lithium ion source case. Notice the slight difference between the two ^8Li cases, which is only marginally enhanced for the binned case for large $\Delta m_{\text{new}}^2 (> 7 \text{ eV}^2)$. (Small) corrections from ions decaying to the ground state of the daughter nucleus are thus expected to be important only in the large Δm_{new}^2 case. The results of Figure 4 show the importance of an appropriate binning.

For comparison we have also included, in these figures, shaded regions corresponding to the 99% C.L. inclusion domains identified by the combination of data from the reactor neutrino experiments and other sources as described in, and here adapted from, Fig. 8 of Ref. [4]. One can see that the proposal investigated here would allow to cover most of the active-sterile oscillation parameter region. On the other hand we recall that the presented exclusion curves have the following simple physical meaning: an actual measurement lying inside the curve (to the upper-right of the curve) represents definite evidence in favour of the corresponding hypothesis, in our case, active neutrinos oscillating into sterile ones. In this manner, from Figure 4 one sees that the shaded region is out of reach if one uses $10^{13} \text{ } ^6\text{He/s}$; whereas using $10^{13} \text{ } ^8\text{Li/s}$ one can cover around 70%-75% of the currently allowed region.

We would like to discuss now the impact of the chosen ion intensities on the setup performance. Figure 5 shows how the exclusion plots (and the coverage of the allowed region) changes when varying the ion intensity. In particular, the physics potential, relative to our main setup with 10^{13} ions/s , is seen to diminish (increase) by changing the intensity in one order of magnitude. This speaks of the high level of influence, that achieving good ion production levels nearby future radioactive ion beam facilities have, upon these type of experimental searches.

Finally, the sensitivity of the proposed experiment might depend upon the achieved systematic errors. To show their impact, we present exclusion curves based upon a binned analysis for sterile neutrino mixing parameters, for different levels of systematic errors. Figure 6 show the impact of 1%, 2%, 5% and 10% systematic error on the exclusion curves for $10^{14} \text{ } ^8\text{Li/s}$. One can see the important impact that reaching low systematic errors has, especially for

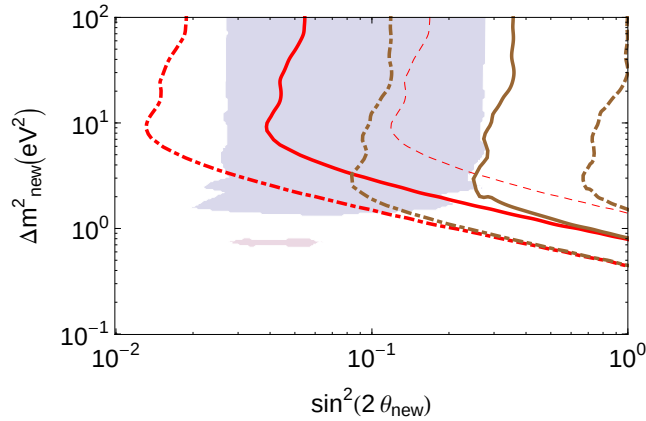


Figure 5. The same as the previous figure but varying the ion intensity: 10^{14} ions/s (dashed-dotted), 10^{13} ions/s (solid) and 10^{12} ions/s (dashed). The red lines correspond to the source of ^8Li ions decaying mainly to the first excited state of the daughter nucleus (maximal neutrino energy 13 MeV); while the brown lines correspond to the source of ^6He ions.

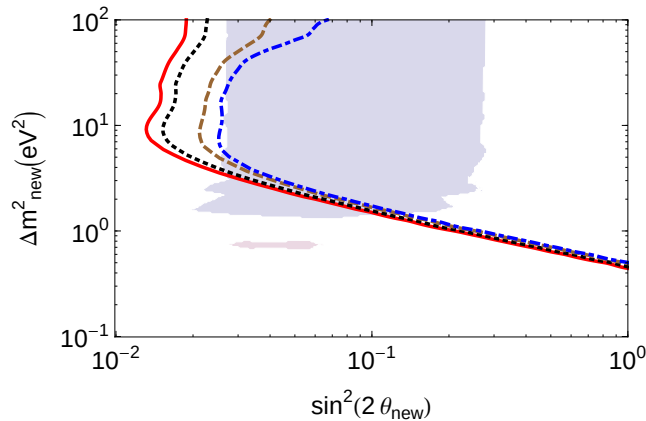


Figure 6. Exclusion plots with binned analysis of the simulated data, obtained for the 10^{14} ions/s with ^8Li ions decaying mainly to a 13 MeV excited state of the daughter nucleus. The figure shows the impact on the exclusion curves of different levels of systematic errors, namely 1% (solid, red), 2% (dotted, black), 5% (dashed, brown) and 10% (dashed-dotted, blue).

large Δm^2 and small mixing angle.

5. Conclusions

Future intense radioactive ion beam facilities can offer a unique opportunity to perform searches for beyond the Standard Model physics, using low energy neutrino fluxes from beta-decaying ions. Here we consider two configurations, where either the ions are stored in a storage ring, or they are sent into a target inside a spherical detector, filled in with a scintillator (with the addition of Gadolinium). Our results show that, as long as the ions are not boosted, the spherical geometry scenario gives better results than the storage ring one. We have considered a sterile neutrino search, that can be performed using electron anti-neutrino detection through inverse beta-decay in a scintillator. We have presented exclusion plots obtained from total rates and from analysis including spectral information of the simulated data. In particular, the binned

analysis gives interesting results for ion intensities achievable at future radioactive ion beam facilities, like e.g. the EURISOL facility. Clearly the ion intensities achievable at such facilities are lower than the MCi radioactive source considered in proposals like the one in Ref.[23]. However radioactive ion beam facilities offer the possibility to dispose of radioactive ions with different Q-values, allowing to cover different regions of the oscillation parameters. With our spherical setup, one can probe large squared-mass differences and rather small mixing angle values, associated with one sterile neutrino, in the 3+1 oscillation framework. In particular, with the kind of setup we consider here, one could confirm/rule out the sterile neutrino hypothesis, as a possible explanation of the currently debated reactor neutrino anomaly, and cover most of the corresponding parameter space region.

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