IOP Concise Physics

Sterile Neutrino Dark Matter

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Chapter 8

The needle in the dark haystack—experimental attempts

The most beautiful theory in physics is not worth much without any experimental evidence. This is a problem theoretical physics faces on a regular basis. Indeed, while we push our theories forward, we should not forget that experimental testability is one of the key factors in physics. In what concerns keV sterile neutrinos, we have seen that they can have a detectable impact on astrophysical environments and on cosmic structure formation. If our data improves in these fields, we may already have a possibility not only to indicate the existence of sterile neutrinos but even to potentially distinguish different production mechanisms. But what is the situation for lab-based experiments?

In a nutshell, as should be evident by now, this is quite a challenge. Basically all lab-based direct searches for keV sterile neutrinos have to rely on the tiny active-sterile mixing. Even worse, in fact only the mixing with the electron-sector can at all be probed, due to all sufficiently stable isotopes not involving any charged leptons beyond electrons (because of the energy scales involved). Nevertheless, several experimental collaborations have been formed which hunt for keV sterile neutrinos. We will in this chapter first discuss the possibilities that are inspired from experiments on the active-neutrino mass, namely trying to constrain keV sterile neutrinos either by their impact at the β-decay spectrum (section 8.1) or on the branching ratios of electron capture decays (section 8.2). A newer and maybe promising idea is based on keV sterile neutrino capture on stable isotopes, see section 8.3, which is not yet investigated at the same detailed level but which has the huge advantage of being scaleable. However, at the moment, all these attempts seem not to be able to probe relevant parameter space. Finally, in section 8.4, we will comment on which conclusions can be drawn from on-going active-neutrino experiments and summarise how future experimental constraints may influence the keV sterile neutrino Dark Matter parameter space.

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8.1 Single beta decay

Let us start with the simplest process. Ordinary β^--decay typically proceeds by a nucleus changing its atomic number by one unit,

$$(Z, A) \to (Z+1, A) + e^- + \bar{\nu}_e, \tag{8.1}$$

in which process a highly relativistic electron is emitted along with an electron antineutrino. However, as we have already learned in chapter 2, an electron neutrino is *not* a mass eigenstate and, thus, it cannot be a proper external state in any reaction. Instead, we have to view it as a superposition of several mass eigenstates, $\nu_{1,2,3}$. Furthermore, if the Q-value (i.e. the energy release) of the decay is large enough for a given isotope, this may also produce the heavy mass eigenstate N_1 (or possibly an anti-version, $\overline{N_1}$), which is predominantly sterile. Of course, the amplitude for this to happen will be suppressed by a factor of $\sin\theta_{e,4}$, see the cartoon on the left of figure 8.1.

But how could we measure the emission of a sterile neutrino? Fortunately, a nearly suitable experiment already exists! First, it is important to realise that, in fact, there is not much of a principle difference between measuring the active or sterile neutrino masses. In both cases, while the neutrino cannot be measured directly, its production will also affect the spectrum of the electrons involved in the decay. It is just that, due to the different mass of the sterile neutrino compared to the active ones, this modification will be visible at a different energy. In the right panel of figure 8.1, we depict the relevant case of tritium decay, with a Q-value of 18.6 keV. While active neutrinos would modify only the endpoint of the spectrum, the influence of a keV sterile neutrino is two-fold: on the one hand, since the presence of a sterile neutrino affects the unitarity of the active-neutrino part of the mixing matrix, there is an overall reduction of the decay rate; on the other hand, since the sterile neutrino can only be produced once the electron only carries away a small enough part of the energy, a kink in the spectrum appears somewhat closely to the sterile neutrino mass (taken to be 10 keV in the example shown). This is crucial because, while an overall reduction of a decay rate may be down to all kinds of effects (such as uncertainties on the nuclear physics involved) and since it is tiny in any case (note that it is strongly

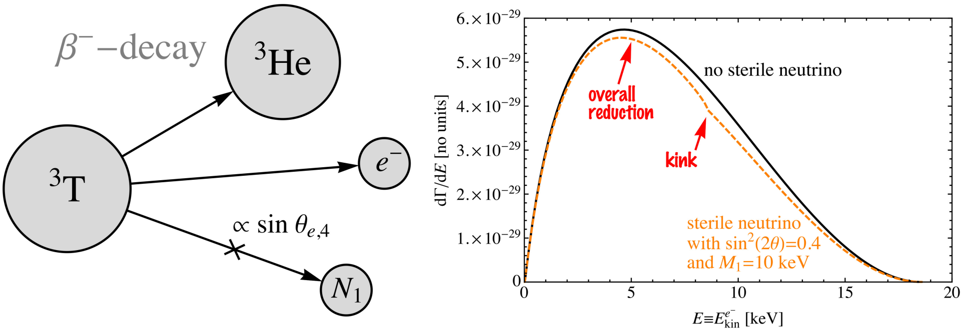

Figure 8.1. The process of β^--decay involving a sterile neutrino (left) and the possible effect of a sterile neutrino on the spectrum as a function of the electron kinetic energy $E^e_{\rm kin}$ (right).

exaggerated in the example shown in figure 8.1), a kink in the spectrum can possibly be observed by taking a differential measurement of the full spectrum.

Which experiment can do this job? As it appears at the moment, the only upcoming such measurement will be performed by KATRIN [1], which is basically a spectrometer for electrons close to the kinematic endpoint of tritium beta decay. In a nutshell, this means that the energy of the most highly energetic electrons released is measured very precisely, because for those the neutrino emitted in the decay will basically be at rest—thus, its mass directly shows up in the energy balance. Experimentally, this is achieved by the electrons passing through a very complicated configuration of magnetic fields (called 'MAC-E filter'), which carefully selects only the fastest electrons. They will then ultimately be subjected to a retarding potential created by a suitable voltage applied (colloquially speaking, they have to climb up a steep hill) and, depending on their energy, they may finally be detected. By varying this voltage and counting the electrons at the detector, one can then determine the number of electrons for a given kinetic energy.

However, the problem is that KATRIN is truly dedicated towards active neutrinos, and it basically discards all electrons with an energy away from the kinematic endpoint. Furthermore, it only has to handle very few electrons, since the number of events is strongly suppressed at the endpoint. For a keV sterile neutrino, instead, one would need to detect the full spectrum, which means that many more electrons have to be counted at a given time. Furthermore, the measurement of the spectrum should be very accurate, to detect the tiny modification induced by small active-sterile mixings. These different requirements were the main reasons to propose the TRISTAN upgrade of the experiment [7], which tries to overcome all difficulties by basically switching off the retarding potential, considerably modifying the MAC-E filter, and using a detector based on semiconducting material (silicon, to be precise) to perform the energy measurement. Such a detector has the great advantage of a very good energy resolution (~1%), however, it is clear that this requires a major upgrade of the existing facilities.

Thus, the question is, how much do we gain? We will see in section 8.4 how far this could reach.

8.2 Electron capture decays

The next generic possibility, again inspired from attempts to measure the active-neutrino mass, is to investigate electron capture reactions. In this process, a bound electron in an atom is absorbed by the nucleus, which then emits an electron neutrino ν_e or, rather, a superposition of the mass eigenstates available. Similarly as before, such a reaction can also produce a sterile neutrino N_1 as long as the energy release is sufficiently high, see the left panel of figure 8.2. However, just as for single beta decays, the emission of that particle is suppressed by a small factor of $\sin\theta_{e,4}$ in the amplitude.

Given that bound electrons have discrete energy levels, the resulting neutrino spectrum (and also the nuclear recoils) will also be discrete, up to the widths of the bound states. Thus, if the energy release is measured in a calorimeter, then the

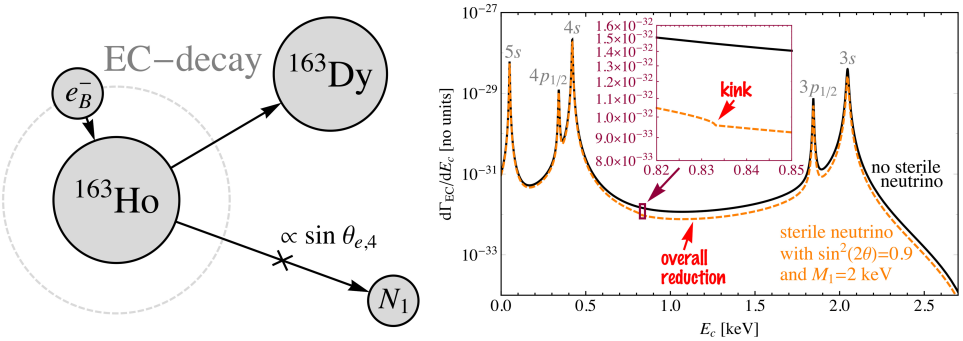

Figure 8.2. The process of electron capture (EC) involving a sterile neutrino (left) and the possible effect of a sterile neutrino on the spectrum as a function of the calorimetric energy E_c measured by the detector (right).

corresponding spectrum should be a collection of smeared peaks, at different energies depending on the shell from which the electrons are captured. The example of holmium decay is depicted in the right panel of figure 8.2, featuring a Q-value so small that electron capture can only proceed from the 3s shell or from even higher orbits. Again, the effect of the sterile neutrino is on the one hand an overall reduction of the spectrum and on the other hand a kink in the vicinity of the sterile neutrino mass. However, note that the effect here is not visible too well in the plot, because of the log-scale used for the y-axis. Thus, in order to at all visualise the effect in the figure, we have chosen a ridiculously high value (i.e. nearly maximal) for the active-sterile mixing angle. However, in reality, the effect is of a strength similar to the case of single beta decay.

The upcoming experiment performing such a measurement is called ECHo [3], which is based on the use of metallic magnetic microcalorimeters operated at low temperatures. This basically means that the detector is identical to the source, and what is measured is the total energy release inside the source (except for the part carried away by the emitted neutrino). In order to get precise information about the neutrino mass, no matter if active or sterile, it is indispensable to have precise knowledge of the Q-value of Ho-163. However, typically, the values found in the literature are not known accurately enough for such a delicate task as the determination of the neutrino mass. This problem was solved by independently measuring the relevant Q-value by Penning traps [2], which resulted into a value of 2.833 keV. Thus, for a sterile neutrino mass below that number, one can in principle use electron capture reactions to search for these particles.

The obvious problem with this kind of measurement, as we have already seen in chapter 6, is that sterile neutrino masses below 3 keV are not very likely, given that all known Dark Matter production mechanisms yield lower bounds on the mass which are larger than that. Nevertheless, if the structure formation bounds were not as tight as we currently think, or if an entirely new production mechanism was proposed, then an experiment like ECHo could nevertheless potentially probe relevant parameter space. We will see in section 8.4 how ECHo compares to other experiments.

8.3 Sterile neutrino capture on stable nuclei

The two methods described both have the problem of the lifetimes of the unstable isotopes being too large, which limits the event rates (i.e. the statistics) and hence the possible discovery reach. Given that long lifetimes are associated with small Q-values, this is not entirely bad, since the sterile neutrinos emitted will have a more visible influence on the spectrum. However, even with that bonus, the problem remains that low lifetimes can only be compensated by large amounts of material—which is precisely what is not desirable to have of radioactive substances. Thus, the experiments described above have the massive drawback of not being *scaleable*.

Thus the question arises where one could possibly attempt a measurement based on non-radioactive material (or, at least, material whose radioactivity does not supersede natural activity levels). Indeed, a proposal for such an experiment has recently been put forward in [4]. The basic idea is the following: imagine there is an isotope that is 'just' stable, i.e. it has a Q-value which is negative but with a very small absolute value. While such an atom or nucleus could not decay spontaneously, it may still be able to 'capture' an incoming sterile neutrino, supposing its energy is large enough to provide the missing bit necessary for the transition. While such an endeavor is probably hopeless for detecting (non-relativistic) active or eV-scale sterile neutrinos, due to their small mass, this may be different for a sterile neutrino with a mass of a few keV. If the energy balance was positive, then such a capture reaction could take place in the way illustrated on the left of figure 8.3.

Does an isotope with suitable properties exist? In fact, we have already seen a similar situation for Ho-163, whose Q-value was so small that only capture from the $3s$ shell or even higher orbits was energetically possible. Thus, we may wonder whether its decay product, Dy-163, could do the job. Indeed, this isotope is only just stable—to the point that, if fully stripped of electrons, it can undergo bound-stand beta decay back to Ho-163, with a final-state electron in one of the first two shells. Indeed, with a Q-value of $Q_{\text{capt}} = -2.833$ keV, dysprosium looks just about right for such a measurement to be undertaken. In principle, one would only need to place

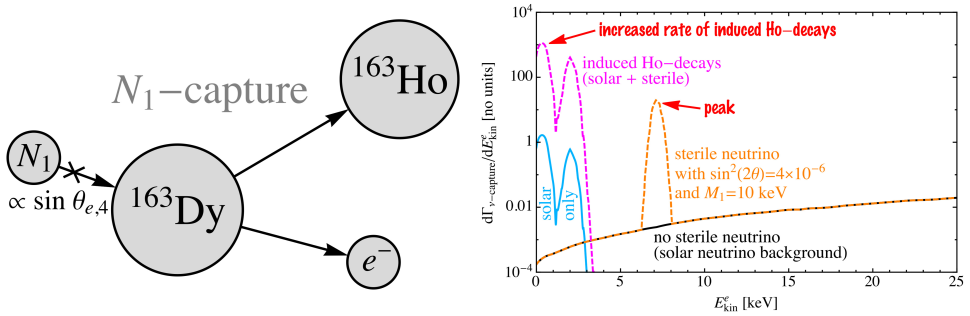

Figure 8.3. The process of sterile neutrino capture on a stable target (left) and the corresponding spectrum (right), with the data for the latter taken from [4].

large amounts of Dy-163 somewhere (or have them already present, e.g. in natural rocks) and wait for the Dark Matter particles to produce Ho-163. This would work since, geologically, no abundance of Ho-163 can be expected—it would all have decayed by now unless there is a constant source refueling it, such as scattering by keV sterile neutrinos. If one then can either detect the Ho-163 production, measure its decay rate, or at least count the holmium atoms produced (which is technically feasible even for single atoms!), then one can in turn constrain the mass and mixing angle of the sterile neutrino, which is what drives the production rate of Ho-163.

Thus, there are different methods to possibly perform such a detection of keV sterile neutrinos. There is an intrinsic background, however: neutrinos emitted from our Sun can in principle also have high enough energies to induce the transition from Dy-163 to Ho-163. While an experiment without any background is always easier to perform than one with background, in this case there may also be an advantage to it: given the characteristic shape of the solar neutrino spectrum, it can possibly even be used to minimise uncertainties associated with the nuclear physics part of the transition. But, in any case, as long as one can perform a real-time measurement of the dysprosium–holmium transitions (e.g. by a calorimeter, in which the energy deposition resulting from the generated electron is measured), the experiment should exhibit a peak in energy at an electron kinetic energy of $E^e_{\text{kin}} = M_1 - |Q_{\text{capt}}|$. By a finite energy resolution, this peak will be broadened a little, but realistic estimates of resolution in the 0.5 keV ballpark show that nevertheless a visible peak should remain in the spectrum on top of the continuous spectrum of transitions induced by solar neutrinos—see the right panel of figure 8.3. Also depicted in this figure is the electron capture spectrum of the Ho-163 isotopes produced (as a function of the calorimetric energy E_c in that case), whose normalization depends on whether sterile neutrinos contribute to the production of holmium, or not. Thus, in addition to directly observing the peak associated with N_1-capture, one could also measure the number of Ho-163 decay in a harvested block of Dy-163, which would have been exposed to the sterile neutrino flow from them being Dark Matter for geological times.

At first sight, this idea seems to be more promising than the previous two, at least from the fact that this approach, based on non-radiative material, is *scaleable*. However, admittedly, this proposal is currently in its initial stages. Let us see in the next subsection how the different ideas compare to each other.

8.4 Drawing conclusions from active-neutrino experiments and getting a global picture

Having discussed a few methods to directly detect keV sterile neutrinos, or at least their influence on certain transitions, we would like to briefly comment on whether we can learn something from active-neutrino experiments. After all, sterile neutrinos are intimately connected to the active-neutrino sector, as we have seen in chapter 2, and the corresponding experiments are in parts even running. Can we hence learn anything from the observables (to be) measured for active-neutrinos?

While in principle the answer to this question must be ‘yes’, due to active and sterile neutrinos being entangled, it will be hard to draw any conclusions in practice. One idea discussed in the literature has been that the mass pattern of active neutrinos may be reflected in the mass pattern of sterile neutrinos. This would indeed be the case if the active-neutrino masses simply arose from a seesaw type I framework, as discussed in section 2.2. Such a situation would in fact be given in the νMSM, whose peculiar sterile neutrino mass pattern requires one of the active neutrinos to be quasi-massless. Thus, given that on-going experiments (or cosmological observations) could potentially show light neutrino masses to be quasi-degenerate (i.e. $m_1 \simeq m_2 \simeq m_3$), this setting could by that observation in principle be excluded [5]. On the other hand, even that only holds under particular circumstances (namely the absence of CP violation in the neutrino sector) and, after all, it would in any case just constrain one particular scenario. Another possibility would be to investigate the value of the effective mass $|m_{ee}|$ as probed in neutrinoless double beta decay, which would in general also be influenced by the presence of sterile neutrinos. On the other hand, that also turns out to be an invisible influence even under very optimistic assumptions [6], which derives from the fact that the x-ray bound on the active-sterile mixing is so strong (see section 7.1).

Hence, when trying to get a feeling for the reach of future experiments, it is sufficient to at first order only consider the experiments discussed in sections 8.1–8.3. This is done in figure 8.4, where we have displayed the same parameter range as in figures 6.3 and 7.2, just this time with only the Tremaine–Gunn, overclosure, and x-ray bounds displayed in addition, in order not to make the plot too busy yet.

First of all we can see that, at the moment, in fact *none* of the possible experiments described is able to even overcome the overclosure limit: thus, if sterile

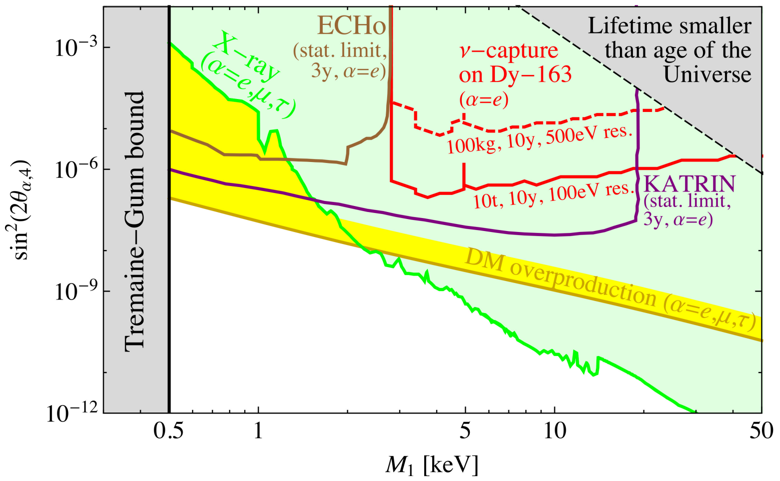

Figure 8.4. Sensitivities of various ground-based experiments.

neutrinos existed with the properties accessible by experiments, they would have been produced in vast amounts in the early Universe by simple non-resonant production (section 4.2). However, once produced, we could not get rid of those sterile neutrinos anymore both due to their feeble interactions (section 2.3) and due to them decaying only very slowly (section 7.1). Thus, in that case, they would have completely overclosed the Universe and it would have been collapsed before mankind even came into existence. While it is fortunate for us that sterile neutrinos, if they exist, certainly do not have these properties, this is also what makes any experimental attempts rather challenging.

Still, at least we can obtain complementary bounds for what we otherwise only know from cosmology and astrophysics. Looking at the sensitivities displayed, we can see that ECHo (KATRIN/TRISTAN) can do this job for sterile neutrino masses below 2.833 keV (18.6 keV), with the mass ranges being limited by the Q-value of the respective reaction. In that sense, keV sterile neutrino capture on dysprosium is nicely complementary to these two approaches, given that it, in contrast, needs the sterile neutrino mass to be *larger* than 2.833 keV.

But how far can we go in terms of active-sterile mixing? For electron capture and single beta decay, the scaling is rather easy: a bigger mixing angle yields a bigger influence, as does a bigger mass (within the allowed range), so that these experiments benefit from comparatively 'heavy' sterile neutrinos. Still, even for rather optimistic assumptions, electron captures will only be able to go down to, about, $\sin^2(2\theta_{e,4}) \sim 10^{-6}$.[1] Experiments on single beta decays could possibly go one order of magnitude further (albeit for a different mass range), however, also that does not even come close to cosmological bounds. This is at least slightly different in case future experiments try to search for sterile neutrino capture. While also here a larger mixing angle is easier to detect, the method would in fact *benefit* from keV sterile neutrinos being on the lighter side, since this would imply a larger number density of them in the Universe (assuming that they make up all, or at least a decent fraction, of the Dark Matter)—thus the 'dip' of the corresponding sensitivity curve at $M_1 \sim 5$ keV. Still, at least in current considerations, this method also does not seem to be able to go much further than KATRIN/TRISTAN. Nevertheless, we want to stress once more that the approach of sterile neutrino capture can at least in principle be scaled, which may one day provide the key for the world-record laboratory bound on the active-sterile mixing angle.

Yet, even when being as optimistic as possible, we can quite generally state that for masses above, say, 10 keV, we cannot expect lab experiments to yield any competitive bound, unless some completely revolutionary idea arises. Still, performing at least some of the above experiments will strengthen our picture and, after all, experiments have often in history led to surprises that the scientific community did not anticipate.

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[1] Note that, for all experiments, only the mixing with the electron sector can be constrained, due to only electrons being present in ordinary matter. In contrast, the x-ray and overclosure bounds hold for mixing with *any* sector.

References

[1] Angrik J *et al* 2004 KATRIN design report 2005. *FZKA-7090*

[2] Eliseev S *et al* 2015 Direct measurement of the mass difference of ^{163}Ho and ^{163}Dy solves the Q-value puzzle for the neutrino mass determination *Phys. Rev. Lett.* **115** 062501

[3] Gastaldo L *et al* 2014 The electron capture ^{163}Ho experiment echo: an overview *J. Low Temp. Phys.* **176** 876–84

[4] Lasserre T, Altenmueller K, Cribier M, Merle A, Mertens S and Vivier M 2016 *Direct Search for keV Sterile Neutrino Dark Matter with a Stable Dysprosium Target* arXiv:1609.04671 [hep-ex]

[5] Merle A 2012 Constraining models for keV sterile neutrinos by quasi-degenerate active neutrinos *Phys. Rev.* D **86** 121701(R)

[6] Merle A and Niro V 2013 Influence of a keV sterile neutrino on neutrinoless double beta decay: How things changed in recent years *Phys. Rev.* D **88** 113004

[7] Mertens S, Lasserre T, Groh S, Drexlin G, Glueck F, Huber A, Poon A W P, Steidl M, Steinbrink N and Weinheimer C 2015 Sensitivity of Next-generation tritium beta-decay experiments for kev-scale sterile neutrinos *JCAP* **1502** 020