Recent results from cosmology and neutrinoless double beta decay

Stefano Dell’Oro, Simone Marcocci

INFN, Gran Sasso Science Institute, Viale F. Crispi 7, 67100 L’Aquila, Italy
E-mail: stefano.delloro@gssi.infn.it, simone.marcocci@gssi.infn.it

Abstract. We quantify the impact of cosmological surveys on the search for neutrinoless double beta decay (0\(\nu\beta\beta\)) within the hypothesis that the 0\(\nu\beta\beta\) rate is dominated by the Majorana mass of ordinary neutrinos. In particular, we exploit the potential relevance of the work of Palanque-Delabrouille et al. [JCAP 1502, 045 (2015)], whose result seems to favor the normal hierarchy spectrum for the light neutrino masses. The impact of our analysis for the future generation of 0\(\nu\beta\beta\) experiments is quite dramatic and motivates further cosmological studies, both theoretically and experimentally. In fact, the allowed values for the Majorana Effective Mass turn out to be \(< 75\) meV at 3\(\sigma\) C. L, lowering down to less than 20 meV at 1\(\sigma\) C. L.

1. Introduction

Neutrinoless double beta decay (0\(\nu\beta\beta\)) [1] is a key tool to address some of the major outstanding issues in neutrino physics, such as the lepton number conservation and the Majorana nature of the neutrino. The discovery of 0\(\nu\beta\beta\) would also provide precious information on the neutrino mass scale and ordering.

The decay half-life, which is the parameter actually probed by experiments, can be factorized as follows:

\[
\left[ t_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |f|^2
\]

(1)

where \(G_{0\nu}\) is the phase-space factor (PSF), \(\mathcal{M}_{0\nu}\) is the nuclear matrix element (NME) and \(f\) contains the physics beyond the Standard Model that could explain the decay. From the theoretical point of view, there can be different mechanisms describing the 0\(\nu\beta\beta\) decay [2]. If ordinary neutrinos dominate the transition, it is convenient to define the so-called “Majorana mass”:

\[
m_{\beta\beta} = m_e |f| \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|.
\]

(2)

Here, \(U_{ei}\) are the elements of the mixing matrix defining the electron neutrino composition and \(m_i\) are the masses of the individual \(\nu_i\). The electron mass \(m_e\) is taken as a reference.

2. Bounds on the Majorana mass

Thanks to the knowledge of the oscillation parameters [3], it is possible to constrain \(m_{\beta\beta}\). However, since the complex phases cannot be probed by oscillations and are unknown, the
allowed region for $m_{\beta\beta}$ is obtained letting them vary freely. A possible graphical representation foresees $m_{\beta\beta}$ as a function of the lightest neutrino mass (see e.g. Ref. [4]). The parameter $m_{\beta\beta}$ can also be expressed as a function of a directly observable parameter. A natural choice is the cosmological mass $\Sigma$ [5], defined as the sum of the three active neutrino masses:

$$\Sigma \equiv m_1 + m_2 + m_3. \quad (3)$$

An experimental limit on the half-life can be translated into a limit on the mass parameter by reversing Eq. 1 and by using the appropriate PSFs [6] and NMEs [7]. At present, the most recent and competitive bounds on $0\nu\beta\beta$ come from $^{76}\text{Ge}$ [8], $^{130}\text{Te}$ [9] and $^{136}\text{Xe}$ [10] and are of the order of $(10^{24} - 10^{25})\text{ yr}$. A graphical representation of the current limits on $0\nu\beta\beta$ is shown in Fig. 1. It is worth to notice that, however, the theoretical uncertainty on the NMEs is huge. This means that the present and future scenarios could worsen very much with respect to what is depicted in Fig. 1. This is mainly due to the possible renormalization (i.e. reduction) of the value of the axial vector coupling constant $g_A$, due to the presence of the nuclear medium. See e.g. Ref. [4] for a discussion on the implications of the “$g_A$ quenching” for the $0\nu\beta\beta$ search.

3. Recent results from cosmology

The indications for neutrino mass from cosmology has kept changing for the last 20 years. In the scientific literature it is possible to find several authoritative claims for a non-zero value for $\Sigma$ but these values cannot be all correct (at least), since they are different among each other. This calls us for a cautious attitude in their interpretation. The subsequent discussion follows the arguments reported in Ref. [15]. In Fig. 2 the values for $\Sigma$ given in Refs. [11, 12, 13, 14] are shown. Referring to the most recent years, two different positions emerge: either we find claims that cosmology provides a hint for non-zero neutrino masses or, instead, very tight limits on $\Sigma$ are obtained. In this brief work, we focus on the latter case. A more complete analysis can be found in Ref. [15]. One of the most recent limit on $\Sigma$ is so stringent, that it better agrees with the $N\bar{N}$ spectrum, rather than with $T\bar{T}$ one [14]. Similar results are obtained in an even newer analysis [16, 17].

Figure 1. The colored regions show the constraints on $m_{\beta\beta}$ from oscillations as a function of the cosmological mass $\Sigma$ with the corresponding the $3\sigma$ regions (due to the oscillation parameter uncertainties). The horizontal lines show the combined experimental limits for the three isotopes mentioned in the text: $^{76}\text{Ge}$ [8], $^{130}\text{Te}$ [9] and $^{136}\text{Xe}$ [10].
Figure 2. Evolution of some significant values for $\Sigma$ as indicated by cosmology, based on well-known works [11, 12, 13, 14]. Since the error for the first value is not reported in the reference, we assumed an error of 50% for the purpose of illustration. The yellow region includes values of $\Sigma$ compatible with the $\mathcal{N}H$ spectrum, but not with the $\mathcal{I}H$ one. The gray band includes values of $\Sigma$ incompatible with the standard cosmology and with oscillation experiments. Figure from Ref. [2]

The tightest experimental limits on $\Sigma$ are usually obtained by combining CMB and Lyman-$\alpha$ forest data. In fact, since they probe different length scales, their combination allows for a more effective investigation of the neutrino induced suppression in terms of matter power spectrum, both in scale and redshift. The limit in Ref. [14] was obtained by using the one-dimensional Lyman-$\alpha$ forest power spectrum extracted from the BAO Spectroscopic Survey of the Sloan Digital Sky Survey (SDSS). In particular, the data from a new sample of quasar spectra were analyzed and a novel theoretical framework which incorporates neutrino non-linearities self consistently was employed. The authors computed a probability for $\Sigma$ that can be summarized to a very a good approximation by [15]:

$$\Delta \chi^2(\Sigma) = \frac{(\Sigma - 22 \text{ meV})^2}{(62 \text{ meV})^2}.$$  

(4)

Starting from the likelihood function $L \propto \exp\left(-\frac{\Delta \chi^2}{2}\right)$ with $\Delta \chi^2$ as derived from Fig. 7 of Ref. [14], one can obtain the following limits:

$$\begin{align*}
\Sigma &< 84 \text{ meV} \quad (1\sigma \text{ C. L}) \\
\Sigma &< 146 \text{ meV} \quad (2\sigma \text{ C. L}) \\
\Sigma &< 208 \text{ meV} \quad (3\sigma \text{ C. L})
\end{align*}$$

(5)

which are very close to those predicted by the Gaussian $\Delta \chi^2$ of Eq. (4). In particular, it is worth noting that, even if this measurement is compatible with zero at less than $1\sigma$, the best fit value is different from zero, as expected from the oscillation data and as evidenced by Eq. (4).

4. Implication for the $0\nu\beta\beta$ search

The close connection between the neutrino mass measurements probed by cosmological observations and those obtained in the laboratory was outlined long ago [18].

In the case of $0\nu\beta\beta$, a bound on $\Sigma$ allows the derivation of a bound on $m_{\beta\beta}$. This can be done by computing $m$ as a function of $\Sigma$ and by solving the quartic equation thus obtained. The resulting plot, by adopting the same representation of Fig. 1, is shown in the left panel of Fig. 3. The free variation of the Majorana phases, together with the uncertainties on the oscillation
Figure 3. (Left) Allowed regions for $m_{\beta\beta}$ as a function of $\Sigma$ with constraints given by the oscillation parameters. The darker regions show the spread induced by Majorana phase variations, while the light shaded areas correspond to the 3$\sigma$ regions due to error propagation of the uncertainties on the oscillation parameters. (Right) Constraints from cosmological surveys are added to those from oscillations. Different C.L. contours are shown for both hierarchies. Notice that the 1$\sigma$ region for the IH case is not present, being the scenario disfavored at this confidence level. The dashed band signifies the 95% C.L. excluded region coming from Ref. [14]. Figure from Ref. [15].

parameters, results in a widening of the allowed regions. Also, the error on $\Sigma$ contributes to the total uncertainty. Its effect consists in a broadening of the light shaded area on the left side of the minimum allowed value $\Sigma(m = 0)$ for each hierarchy (see Ref. [15] for details).

It is possible to include the new cosmological constraints on $\Sigma$ from Ref. [14] considering the following inequality [15]:

$$\frac{(y - m_{\beta\beta}(\Sigma))^2}{(n\sigma[m_{\beta\beta}(\Sigma)])^2} + \frac{(\Sigma - \Sigma(0))^2}{(\Sigma_n - \Sigma(0))^2} < 1$$

(6)

where $m_{\beta\beta}(\Sigma)$ is the Majorana Effective Mass as a function of $\Sigma$ and $\sigma[m_{\beta\beta}(\Sigma)]$ is the 1$\sigma$ associated error, computed as discussed in Ref. [4]. $\Sigma_n$ is the limit on $\Sigma$ derived from Eq. (4) for the C.L. $n = 1, 2, 3, \ldots$ By solving Eq. (6) for $y$, it is possible to get the allowed contour for $m_{\beta\beta}$ considering both the constraints from oscillations and from cosmology. In particular, the Majorana phases are taken into account by computing $y$ along the two extremes of $m_{\beta\beta}(\Sigma)$, namely $m_{\beta\beta}^{\text{max}}(\Sigma)$ and $m_{\beta\beta}^{\text{min}}(\Sigma)$, and then connecting the two contours. The resulting plot is shown in the right panel of Fig. 3.

The most evident feature of the new figure is the clear difference in terms of expectations for both $m_{\beta\beta}$ and $\Sigma$ in the two hierarchy cases. The relevant oscillation parameters (mixing angles and mass splittings) are well known and they induce only minor uncertainties on the expected value of $m_{\beta\beta}$. These uncertainties widen the allowed contours in the upper, lower and left sides of the picture. The boundaries in the rightmost regions are due to the new information from cosmology and are cut at various confidence levels. It is notable that at 1$\sigma$, due to the exclusion of the IH, the set of plausible values of $m_{\beta\beta}$ is highly restricted. Table 1 summarizes the new allowed values for $m_{\beta\beta}$.

The next generation of 0$\nu\beta\beta$ experiments is expected to probe the upper values of the predicted IH region and reach a sensitivity for $m_{\beta\beta}$ of about 70 meV [4]. This assumes the absence of the quenching of the axial coupling constant, which would imply even longer lifetimes and conversely would worsen the sensitivity to $m_{\beta\beta}$ significantly [4].

On the other hand, a 0$\nu\beta\beta$ signal in the near future could either disprove some assumptions of the present cosmological models, or suggest that a different mechanism other than the light
neutrino exchange mediates the transition.

5. Summary
Cosmology is making impressive progress in producing stringent bounds on $\Sigma$. The recent results from Ref. [14] indicate small values for the lightest neutrino mass (the authors find $\Sigma < 84\text{ meV}$ at 1\textsigma C.L.) and provide a 1\textsigma preference for the normal hierarchy. A cautious attitude in dealing with the results from cosmological surveys is, anyway, highly advisable. Furthermore, these results enhance the importance of exploring the issue of mass hierarchy in laboratory experiments.

From the point of view of $0\nu\beta\beta$, the new results show that ton or multi-ton scale detectors will be needed in order to probe the range of $m_{\beta\beta}$ now allowed by cosmology. Nevertheless, if next generation experiments see a signal, it will likely be a $0\nu\beta\beta$ signal of new physics different from the light Majorana neutrino exchange. See Ref. [15] for details.

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