Search for creation of electrons in lab

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Abstract. We examine the physics motivations to search for lepton number violations in the laboratory, in particular by studying the important nuclear transition called neutrinoless double beta decay, which consists in the creation of a pair of electrons. We address some major shortcomings of the Standard Model of electroweak interactions, arguing that most of them can be solved simply within extended models with Majorana neutrinos. At the same time, we discuss the difficulties of obtaining precise predictions for the neutrinoless double beta decay rate and strengthen the case of probing Majorana neutrino masses of about 10 meV.

This report concerns a transition where the nucleus increases its charge by 2 units

\begin{equation}
(A, Z) \rightarrow (A, Z + 2) + 2e^- \tag{1}
\end{equation}

that, by tradition, is called neutrinoless double-$\beta$ decay\textsuperscript{1}, a jargonic name often abbreviated as $0\nu\beta\beta$. Notice that a more modern and fair description of this hypothetical process is simply creation of electrons in a nuclear transition; the traditional name is not equally transparent [1].

This work is based on a series of recent papers on the above transition, which include,

- an inquiry on the effect of nuclear physics uncertainties on the expectations, Ref. [2].
- an investigation of the impact of cosmological bounds of neutrino masses, Ref. [3].
- an extensive review on $0\nu\beta\beta$, Ref. [4].

In these papers and in the present report the leading contribution to the transition of Eq. (1) is attributed to the virtual exchange of light Majorana neutrinos, for the reasons recalled later on.

1. The components of the matter and the corresponding conservation laws

What is the nature of the constituents of Matter? Since the time of ‘Rutherford experiments’ conducted by Geiger and Mardsen [5], we know that any atom is made of heavy components clustered in a small nucleus (the neutrons and protons, classed as baryons), in turn surrounded by light components (the electrons, classed as leptons). The list of the known leptons – i.e., the light components of Matter – was completed later by Pauli, who hypothesized the existence of the neutrino. This particle has only weak interactions with the other particles and it is not in the nucleus, as realized by Fermi. Still, it has to be included among the Matter particles, for it

\textsuperscript{1} Originally (1899) ‘$\beta$-rays’ indicated a specific type of ‘uranium-rays’, then ‘nuclear electrons’ expelled by certain nuclei. This terminology fitted a bygone theory of the nucleus, thought as an assembly of protons and electrons, and abandoned after neutron discovery (1932). Nowadays, the term ‘$\beta$-ray’ is an obsolete synonym of ‘electron’. 
allows us to introduce a quantity that is conserved in any known reaction: the net number of leptons \( L \), strictly analogous to the net number of baryons \( B \).

Much later, it was understood that hadrons are composed by lighter components, the quarks, which are so strongly bound that the largest fraction of the mass of the protons and neutrons is actually their binding energy. The conservation of the number of quarks holds true and implies the one of baryons. In short, to the best of current knowledge, the basic constituents of Matter are quarks and leptons. Over time, it was also understood that quarks and leptons come in three “copies” – families – among which transitions are possible. For quarks it is sufficient to recall the existence of weak decays, while for leptons, one should consider e.g. the \( \nu_\mu \to \nu_e \) transitions observed by T2K [6] or the \( \nu_\mu \to \nu_\tau \) one detected by OPERA [7]. The only known conserved quantities are: 1) the sum of the leptons of the electronic, muonic and tauonic families \( (L = L_e + L_\mu + L_\tau) \); 2) the corresponding total number of baryons \( B \); 3) their combinations.

Is there any observational hint that \( B \) and/or \( L \) are violated at some level? Only one to date, indirect but important. This consists in the fact that the cosmos contains baryons but not any significant amount of anti-baryons. Such a circumstance is actually quite disturbing since in the earliest instants of the Universe, anti-baryons were surely present in large amount. This lead Sakharov to speculate on the existence of fundamental phenomena in which \( B \) is violated, resulting in turn into a cosmic preference for baryons [8]. Twenty years later, it was realized that the same scenario could be attributed to fundamental phenomena where \( L \) is violated [9].

The question whether there exist phenomena observable in laboratory where \( L \) or \( B \) are violated deserves the maximum attention. The most promising way to probe \( L \)-violation is provided by the transition of Eq. (1), both for the experimental reasons discussed in Ref. [4] and for the theoretical motivations recalled in the next section.

2. The SM, seen as the current theory of matter, and its issues

The reference theory of matter today is the Standard Model (SM) of electroweak interactions, or SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ Glashow-Weinberg-Salam gauge theory. This stunningly successful theory has various issues relevant for the present discussion [1], namely:

(i) neutrino masses are zero.
(ii) \( B - L \), \( L_e - L_\mu \), \( L_e - L_\tau \), \( L_\mu - L_\tau \) are exactly conserved while \( B, L, L_e, L_\mu, L_\tau \) only at the first order.
(iii) matter particles are absolutely distinguished – neutrinos included.
(iv) the cosmic excess of baryons cannot be explained.

Even by excluding the last point, it should be noticed that the first prediction is wrong (as recognized by the Nobel Prize in Physics 2015), the second one is mostly wrong (see the discussion in Sec. 1), while the third one is disputable: First of all, neutrinos do not have an intrinsic electric charge that distinguishes them from antineutrinos. Second, the SM has one neutrino and one antineutrino per family with opposite helicity, thus the most economical assumption is that, in the rest frame, these two are just the spin states of the same particle.

Incidentally, it should be remarked that: a) \( B + L \) is not a symmetry of the SM, and this is an important reason why new phenomena where \( L \) and \( B \) are violated have very similar significance; b) the transition of Eq. (1) violates \( L \) and also \( B - L \), so that its existence would have a major impact on the SM: it would prove that none of its symmetries is exact. The previous goal is distinctive of \( \theta\beta\beta \), seen as a potentially measurable transition: it would not be achieved even if we discovered \( p \rightarrow p^0 e^+ \) or \( p \rightarrow K^+ \bar{\nu} \) or any other \( (B - L) \)-conserving nucleon decay mode.

3. A powerful fix for SM issues: the hypothesis of Majorana neutrinos

The breaking of SU(2)$_L \times$U(1)$_Y$ due to the vacuum expectation value \( \langle H^0 \rangle = 174 \text{ GeV} \) determines the Fermi constant \( G_F = 1/(\sqrt{8}(H^0)^2) \) that explains weak decays at much lower energy scales.
Likewise, new physics at a scale $M \gg \langle H^0 \rangle$ can lead to neutrino masses. Indeed, by using the
\begin{equation}
\frac{1}{2} \delta \mathcal{L} = \frac{1}{2} \frac{\kappa_{\ell\ell'}}{M} N_\ell C^{-1} N_{\ell'} + h.c. \quad \text{with} \quad \ell, \ell' = e, \mu, \tau
\end{equation}
where $C$ is the charge conjugation matrix, $\kappa_{\ell\ell'}$ are a-dimensional coefficients and $M$ an explicit
mass scale, needed for dimensional reasons. These terms imply a violation of the lepton number, as it is evident from the fact that they contain two lepton fields – addressing issue (ii) radically.

The previous lagrangian density gives rise to neutrino masses – solving issue (i). In fact,
\begin{equation}
\mathcal{L}_{\text{bil}} = \mathcal{M}_{\ell\ell'} \nu_\ell C^{-1} \nu_{\ell'} + h.c. \quad \text{where} \quad \mathcal{M}_{\ell\ell'} = 50 \text{meV} \cdot \kappa_{\ell\ell'} \left( \frac{6 \cdot 10^{14} \text{GeV}}{M} \right)
\end{equation}
Let us diagonalize the matrix $\mathcal{M}$ by using a unitary matrix $U$: $\mathcal{M}_{\ell\ell'} = U_{\ell i}^* m_i U_{\ell' i}$ with $i = 1, 2, 3$ and $m_i \geq 0$. We can introduce the new fields $\nu_i \equiv U_{\ell i}^* \nu_\ell$, which in turn allow us to define the fields $\chi_i \equiv \nu_i + C \bar{\nu}_i$. The Lagrangian density (3), rewritten with these fields, becomes simply
\begin{equation}
\delta \mathcal{L}_{\text{bil}} = -\frac{3}{2} \sum_{i=1}^3 m_i \bar{\chi}_i \chi_i.
\end{equation}
In other words, the neutrinos described by the $\chi_i$-fields have mass $m_i$. We conclude that physics
beyond the SM at a scale $M \gg 174 \text{GeV}$ can actually lead to values of the neutrino masses $m_1 \simeq 50 \text{meV} = \sqrt{\Delta m_{\text{atm}}^2}$, that are needed in order to explain neutrino oscillations.

The fields with given mass are self-conjugated, $\chi_i = \bar{\chi}_i$ – i.e., they are Majorana fields [12] – thus there is just one type of elementary oscillators with given momentum $p$ and helicity $\lambda$
\begin{equation}
\chi_i = \sum_{\vec{p}, \lambda} \left[ u_{\vec{p}, \lambda} e^{-i p x} a_{\vec{p}, \lambda} + C \bar{a}_{\vec{p}, \lambda} e^{i p x} a_{\vec{p}, \lambda}^\dagger \right]
\end{equation}
Simply stated, these neutrinos are matter and antimatter at the same time: – which fits issue (iii).²

4. Majorana neutrinos and the process of creation of electrons
We are ready to come back to the transition of Eq. (1). The key parameter that regulates its rate is:
\begin{equation}
m_{\beta\beta} \equiv |\mathcal{M}_{ee}| = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|.
\end{equation}
In fact, an evident feature of Eq. (1) is that the electronic lepton number $L_e$ is violated twice, and $\mathcal{M}_{ee}$ is the only element of the neutrino mass matrix which obeys this selection rule.³ Unfortunately, it is not possible to infer its value from the available neutrino data and, even more, a theory of fermion masses is not available yet. This implies that particle physics offers only a qualitative understanding; we have the largest quantitative uncertainty. A reasonable way to proceed in the theoretical discussion is to resort to “educated guesses”. Moving in this direction and following [1, 13] let us postulate that the neutrino mass matrix has the form
\begin{equation}
\mathcal{M} \equiv 50 \text{meV} \times \begin{pmatrix}
\varepsilon & \varepsilon & \varepsilon \\
\varepsilon & 1 & 1 \\
\varepsilon & 1 & 1
\end{pmatrix},
\end{equation}
³ The parameter $m_{\beta\beta} = |\mathcal{M}_{ee}|$ is commonly called effective Majorana mass. For the notation, see again footnote 1.
² Funnily enough, all we need to fix the major SM defects of Sec. 2 is a theoretical proposal appeared thirty years before the formulation of the SM – namely, Majorana neutrino masses.
Figure 1. Monte Carlo analysis of the expectations for $m_{\beta\beta}$ in the model of Eq. (7) with $\varepsilon = \theta_C = 13^\circ$. The $O(1)$ coefficients are sampled uniformly inside the complex circle of radius 1. An expectation of $m_{\beta\beta} \sim \sqrt{\Delta m_{\text{atm}}^2} \times \theta_C \sim 10\text{meV}$ is obtained.

assumed to be known just up to $O(1)$ coefficients that multiply the individual elements. In this scheme, atmospheric neutrino oscillations are accounted for by the overall scale and by the large $\nu_\mu - \nu_\tau$ block. The small mixing $\theta_{13} \sim 8^\circ$ indicates a similar value of the parameter $\varepsilon$. The values of $m_{\beta\beta}$ fall in the ballpark illustrated in Fig. 1, that points out the interest in probing values of $m_{\beta\beta}$ at or below 10 meV. This corresponds to the experimental challenge of designing, building, and operating multi-ton detectors for the $0\nu\beta\beta$ search [4].

5. Constraint on the neutrino masses due to cosmological measurements
When combined together, the precise observations of the large cosmic scales by Planck (via the measurement fo the Cosmic Microwave Background [14]) and those concerning smaller scales, e.g. galaxy distributions, Baryon Acoustic Oscillations or the Lyman-\alpha forest power spectrum, allow us to probe neutrino masses with values far below the electronvolt.\footnote{Several works reported that according to cosmological surveys the sum of neutrino masses, $\Sigma \equiv m_1 + m_2 + m_3$, is smaller than (100 – 200) meV, that, in turn, slightly favors the NH scenario [3]. In a recent work, the authors of Ref. [15] reached analogous conclusions (see Fig. 2) and moreover their best-fit value for $\Sigma$ is close to the allowed minimum, corresponding to $m_{\beta\beta} \lesssim$ a few 10 meV [3, 4]. Such an expectation is consistent with that suggested by the above theoretical argument and, again, points out that multi-ton detectors are necessary for the $0\nu\beta\beta$ search [3, 4]. This conclusion is so significant, that a few cautionary remarks are in order:

• In the past, several well-known works have claimed that the neutrino masses obtained from cosmology were different from zero, as summarized in fig. 8 of [4]. Today, these claims are considered premature and there is a new one [16] compatible with the new tighter limits.

• An independent indication in support of the NH case derives from the global analyses of the oscillation data [17] - note however that oscillations do not probe the absolute mass scale.

• The existence of other physics (besides Majorana neutrino masses) where $L$ is violated in a potentially relevant manner can be probed at LHC.

In other words, it is important to be aware that the discussion is still evolving. Let us repeat that these considerations are based on the Majorana neutrino mass hypothesis, which implies the correlation between the rate of Eq. (1) and cosmological measurements.

6. The role of nuclear physics
The amplitude of the transition of Eq. (1) depends linearly upon $m_{\beta\beta}$ and the corresponding half-life time can be factorized as

$$[t_{1/2}]^{-1} = G \times |\mathcal{M}|^2 \times \left(\frac{m_{\beta\beta}}{m_e}\right)^2 \quad (8)$$

\footnote{To get an idea, notice that at the “decoupling”, the temperature of the Universe was 1,100 times larger than the present one, namely $\sim 250\text{meV}$.}
Figure 2. Likelihood $L(\Sigma) \propto e^{-\Delta \chi^2/2}$ with the $\Delta \chi^2(\Sigma)$ obtained in Ref. [15]. The grey area is excluded by the Big Bang cosmology with three massive neutrinos. The 1σ region is consistent with Normal mass Hierarchy (NH) scenario and not with the Inverted Hierarchy (IH) one.

where the electron mass $m_e$ is conventionally chosen for normalization, $G$ is an overall factor that includes the phase space and the effect of the electrostatic field on the emitted electrons, while $M \propto \langle A, Z + 2\mid H_{\text{eff}} \mid A, Z \rangle$ is the matrix element connecting the initial final states of the transition. In particular, the latter arises at the second order of weak interactions $H_{\text{eff}} \propto G_F^2$, where $G_F$ is the Fermi coupling and describes the residual effect of a virtual exchange of a Majorana neutrino.\footnote{It should be noticed that it is common to depict the Feynman diagram of the 0νββ transition in terms of free quarks or occasionally of free nucleons. However, these are poor descriptions of the actual physical situation.} Since the neutrons and the protons are confined inside the nucleus, the virtual momentum of the neutrino is of the order of the inverse nuclear size, $Q \approx 100$ MeV, and it is thus much larger than typical momenta in the known nuclear weak decays.

In a conservative discussion, it is very important to quantify both the expected value of $M$ and the related uncertainty. In fact, the number of signal events in a 0νββ experiment increases quadratically with this parameter whereas the corresponding increase with the detector mass (i.e. with the number of nuclei under observation) is less: linear in the optimistic situation of a background-free experiment, or as the square root of the mass in the presence of background.

7. Uncertainties in the matrix elements and the hypothesis of quenching

Until a few years ago, the uncertainty on $M$ – estimated by comparing the published calculations – was about a factor of a few \cite{18}. More recently, it was noted that, disregarding the Shell Model estimates, the QRPA and the IBM-2 estimates agree in a much better way, within $\sim 30\%$ for several nuclei. This suggested the possibility that the error could actually be of this size. However, when the same calculations are compared with other (measured) transitions, such as the ordinary beta decay, or the two-neutrino double beta decay, the disagreement is much larger and it is found that QRPA and IBM-2 systematically overestimate the matrix elements. These considerations have revived interest for an old hypothesis, namely that the axial coupling of charged current weak interactions, whose value is $g_{\text{axial}} \approx 1.27$ for free nucleons, might decrease for nucleons inside the nuclear matter. It is the so called quenching. Scaling $g_{\text{axial}} \sim 1.27 \cdot A^{-0.18}$ with the mass number $A$, finds a better agreement with the measured rates for the two-neutrino double beta decay \cite{19}. We would like to make a few comments on this important issue:

- it must be stressed that, to date, the quenching hypothesis is \textit{not} a theory but, at most, a phenomenological model.
- if the quenching is real, it should depend upon the exchanged momentum $Q$ and it should disappear for free nucleons. Therefore, since $Q$ is very large in the transition of Eq. (1), the quenching could be much smaller. Indeed, model calculations indicate $g_{\text{axial}} \approx 1$ \cite{20}, which is not as extreme as $g_{\text{axial}} = 1.27 \cdot A^{-0.18}$.
- the hypothesized quenching can be cautiously considered as a factor of uncertainty in the predictions, even if, doing so, the impact on the predictions is quite dramatic \cite{21, 2, 4, 22}.
e.g., for $^{130}$Te, the expected $0\nu\beta\beta$ lifetime would increase as, $\sim 1/g_{\text{axial}}^4$, namely, by a factor 30.

- even if the quenching of $g_{\text{axial}}$ is smaller than the one reported, the effect might be relevant anyway. For example, it was argued in Ref. [4] that a 20% decrease in the value implies a factor 6 increase in the detector mass to compensate for the loss of sensitivity.

In any case, the theoretical calculations cannot be considered definitive yet and, after all, no good reason is known to omit the Shell Model calculations from the general assessment concerning the matrix elements: see Ref. [23] and the discussion at the conference.

8. Summary and assessment

The reasons to search for the transition of Eq. (1) – creation of electrons [1, 24] – are stronger than ever. Particle physics theory helps for general considerations and/or for orientation, e.g. motivating the connection of Majorana neutrino masses and the extension of the SM, pointing out arguments in favor of the NH and/or suggesting ideas on flavor structure of neutrino masses. However, no model of fermion masses can be taken “too seriously”, at least at this point in time.

The measurements of the neutrino oscillation parameters and, possibly, also cosmology give us a real chance to progress in the expectations for the rate of the $0\nu\beta\beta$ transition. The tightest cosmological bounds that have been discussed in the scientific literature require multi-ton detector masses, even for background-free experiments [3, 4].

The theoretical uncertainties on the expected rate are large, mostly due to particle physics, but also to nuclear physics [2, 4]. Fortunately, the importance of the discussion is understood and the situation is possibly evolving in a positive way.

Summarizing, the hypothesis of Majorana neutrino mass remains appealing and points out correlations between the transition of Eq. (1) and other phenomena, such as cosmological observations. However, if new sources of lepton number violation at low energy (TeV?) exist, these correlations could be evaded and surprises may occur: Indeed, $0\nu\beta\beta$ does not probe neutrino masses directly, but just the half-life time of the decay.

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