NEUTRINO-LESS DOUBLE BETA DECAY — *Experimentum Crucis* OF NEUTRINO PHYSICS*

Z. Sujkowski

The Andrzej Sołtan Institute for Nuclear Studies
05-400 Otwock-Świerk, Poland

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The presently most wanted information on neutrino properties concerns their mass values and their transformation properties under charge conjugation. The recent oscillation experiments prove that at least one of the three neutrino species has a non-vanishing rest mass and that the lepton flavour is not conserved. These findings have to be supplemented by data from phenomena of different kind in order to deduce the information needed. The most promising method proposed thus far to determine Majorana neutrino mass and thus to answer the two leading questions is to observe the neutrino-less double beta decay and to measure its rate. The physics of this process is discussed and the on-going and planned experimental search is reviewed. This search concentrates on the $0^+ \longrightarrow 0^+$ ground-to-ground state decay of $\beta^-\beta^-$ emitters using calorimetric or $\beta^- - \beta^-$ coincidence tracking techniques. The $\beta^+\beta^+$ or β^+EC decays are usually considered as less favourable because of longer half-lives, even though they offer some advantages in combating the background. The recent proposition of measuring the monoenergetic photon spectra accompanying the radiative neutrino-less double electron capture decay is discussed. The experimental advantages of this technique may off-set the generally longer life-times expected.

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1. Introduction

The recent neutrino oscillation experiments [1–3] imply that the lepton flavour is not conserved and that at least one of the neutrino species has a finite rest mass.

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One necessary condition for the oscillations to take place is the finite mass difference between neutrinos of different flavour, $m_{\nu_i} - m_{\nu_j} \neq 0$. While an improved set of oscillation data might suffice to determine the mass hierarchy, the phenomenon is insensitive to the absolute values of the masses involved. A piece of data from phenomena of different kind is needed to complete the picture. There are two kinds of experiments being pursued at present to achieve this goal: the direct measurement of the electron antineutrino mass from the end point of tritium β^- spectrum [5] and the indirect determination from the rate of the neutrino-less double beta decay, $0\nu\beta^-\beta^-$ (see *e.g.* [4] and [8] for recent reviews and [6] for the description of a recent experiment). Constraints on the neutrino mass value can also be obtained from cosmological considerations. The present estimate [7], assuming equal population of the three neutrino species, is $m_{\nu_e} + m_{\nu_\mu} + m_{\nu_\tau} \leq 8$eV. The present limit [5] from the tritium spectrum is $m_{\nu_e} < 2.2$ eV; the results of the double beta quest will be described below.

Our appreciation of the role the neutrino plays in the mechanisms governing the Universe has been quickly mounting recently. The neutrino emission is considered nowadays as the main way to cool the newly born stars, the neutrino may take a significant share of the missing dark mass, we calculate the neutrino emission rate from the Sun to be $\sim 2 \times 10^{38}$ neutrinos per second ($\sim 4 \times 10^{10} \nu/\mathrm{scm}^2$ coming to the Earth), we expect that throughout the Space there are about 300 very low energy neutrinos/cm^3 ($E \sim 0.0004$ eV) remembering the Big Bang *etc.* Yet the basic properties of this particle are still to be learnt.

Observing the double beta decay with no accompanying neutrino emission would be a major step in this direction, much larger in fact than merely obtaining a measure of the neutrino mass, however important that is. Such an observation would also prove that not only the lepton flavour but also the lepton number is not conserved and, moreover, that neutrino is a Majorana (two spinor) and not a Dirac (four spinor) particle and thus that it is identical to its charge conjugate, *i.e.* that $\nu \equiv \bar{\nu}$. Both facts would have far reaching consequences for our understanding of weak interactions.

The double beta decay is a very slow process, unobservable practically in the presence of the single β decay to the adjacent isobar. It may be observed, however, whenever the single beta decay of an even nucleus is energetically impossible while there is a positive mass difference for isobars with neutron or proton numbers differing by two units. Thus we may have processes

$$(Z,N) \to (Z+2, N-2) + e_1^- + e_2^- + \bar{\nu_e} + \bar{\nu_e}\,, \tag{1}$$

or

$$(Z,N) \to (Z-2, N+2) + e_1^+ + e_2^+ + \nu_e + \nu_e + 2e^-_{\mathrm{atomic}}\,, \tag{2}$$

with the double electron capture alternative

$$(Z,N) \to (Z-2,N+2) + \nu_e + \nu_e \,. \tag{3}$$

This is illustrated in Fig. 1 showing the mass parabola for A = 76, 92, 100, 144 and 180. There are two candidates shown for the $\beta^-\beta^-$ decay, namely ^{76}Ge and ^{100}Mo, and three for the $\beta^+\beta^+$ or double electron capture

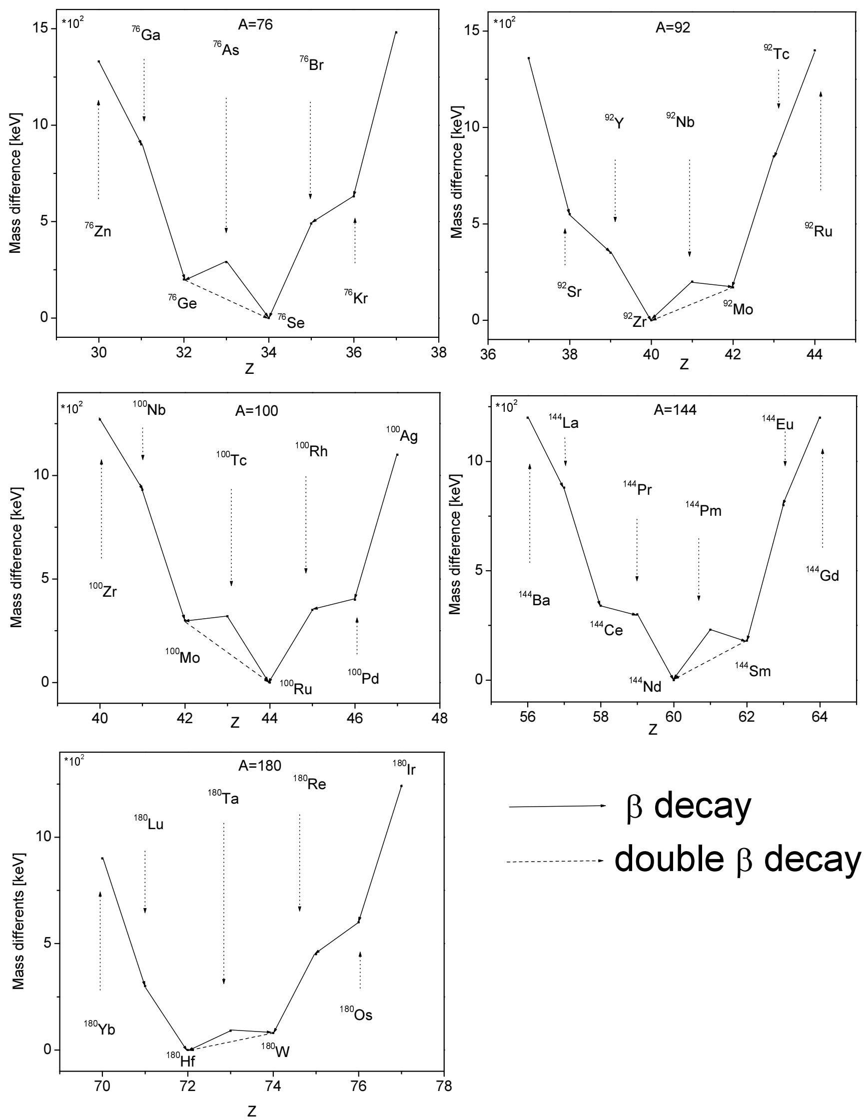

Fig. 1. Mass parabola for selected isobar chains.

transitions: ^{92}Mo, ^{144}Sm, and ^{180}W. The first two are subjects of the most ambitions projects being pursued at present (see Section 4). The remaining three are candidates for studies with the recently proposed novel technique of looking for the photon radiation accompanying the neutrino-less double electron capture (see Section 5).

The possibility of a detectable double β decay has been recognised as early as in 1935 by Goepert-Mayer [9]. She gave the life-time estimate

$$\tau(2\nu\beta^-\beta^-) \geq 10^{20} y\,. \tag{4}$$

Soon after, in 1937, Majorana [10] has proposed his famous $\nu \equiv \bar{\nu}$ and the same year Racah [11] suggested the possibility of neutrino-less double β transitions. With parity assumed to be conserved, the rate for this $0\nu\beta^-\beta^-$ decay was expected to largely exceed that for $2\nu\beta\beta$ processes [12]. Unfortunately, the reverse is true. The helicity arguments slow down the neutrino-less decay rate very considerably, in proportion to ${m_\nu}^2$. This on the one hand provides a tool to determine m_ν, but on the other it makes this determination extremely hard to carry out.

2. Dirac and Majorana fermions

According to the Majorana's suggestion a massive fermion having no additive quantum numbers and being identical to its charge conjugate can be described as a two component object with either left-handed or right-handed chirality eigenstates. A detailed discussion of the distinction between the Dirac and Majorana neutrinos can be found in *e.g.* [8]. For the purpose of the present article we shall recapitulate only the rudimentary helicity (handedness) and chirality arguments, as these are crucial for predicting the salient features of the neutrino-less double beta decay phenomenon.

The difference between neutral particles and antiparticles is not obvious. We may notice that these objects are identical in the case of the neutral pion, $\pi^0 \equiv \bar{\pi}^0$, but not in the case of the neutral kaon, $K^0 \neq \bar{K}^0$. This need not be regarded as astonishing since the pions as well as the kaons can be considered as composite particles, not truly elementary: they are bosons composed of charged fermions, the quarks and antiquarks. The essential in this respect is that strongly and/or electromagnetically interacting particles have different transformation properties under charge conjugation, C, for Dirac and Majorana objects. This is not the case for neutrinos, which, according to our present knowledge, interact only weakly (though a Dirac neutrino, in contrast to the Majorana one, may have a magnetic moment). Weak interactions are not invariant under charge conjugation, they mix the eigenstates of C. Thus, rather than defining a Majorana particle by its transformation properties under the charge conjugation, we should generalise this definition to transformation properties with respect to other discrete symmetries or combinations thereof, such as CP or CPT. The chiral properties of the neutrino states should be explicitly taken into account in the transformation.

Fig. 2 illustrates the different behaviour of a massive left-handed Dirac and Majorana neutrino, ${\nu_{\rm L}}^{\rm D}$ and ${\nu_{\rm L}}^{\rm M}$, under Lorentz transformation. As the velocity of a massive neutrino is lower than c, the Lorentz transformation turns $\nu_{\rm L}$ into a right handed ν_R. The corresponding two CPT images are $\bar{\nu}_R$ and $\bar{\nu}_{\rm L}$. As a result we have four states of equal mass, representing the Dirac neutrino, $\nu^{\rm D}$. The Majorana suggestion states that the right handed particle obtained by the Lorentz transformation of $\nu_{\rm L}$ to a faster moving reference frame is identical to the CPT image of $\nu_{\rm L}$. There are thus only two states with the same mass. These represent the Majorana neutrino, $\nu^{\rm M}$.

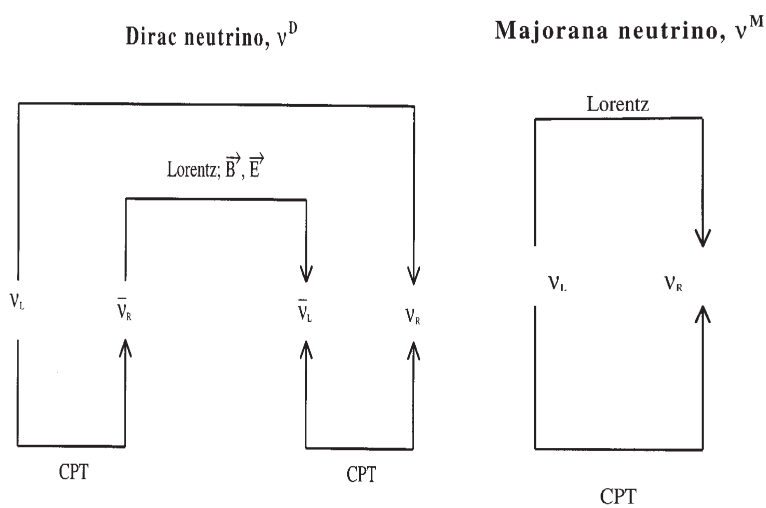

Fig. 2. Different behaviour of massive left handed Dirac and Majorana neutrino under Lorentz transformation.

3. Neutrino-less double beta decay

Fig. 3 shows the Feynman diagrams for normal beta transformations of a neutron into a proton and of a proton bound in the nucleus (N, Z) into a neutron in the nucleus $(N+1, Z-1)$. The corresponding diagram for $0\nu\beta^-\beta^-$ Majorana decay is depicted in Fig. 4(a). The left-handed neutrino emitted by one neutron is absorbed by another with an amplitude proportional to the proper helicity admixture and thus to the neutrino mass. Only two electrons appear in the continuum in the final state. In the case of

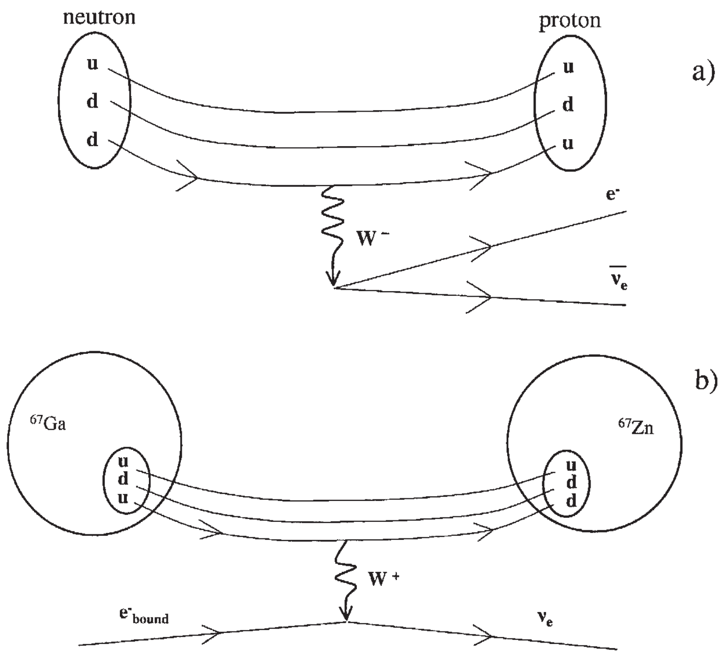

Fig. 3. Feynman diagram for beta decay of a free neutron (a) and for electron capture to a proton bound in ^{67}Ga nucleus (b).

the Dirac neutrinos there would be two ν_L in the continuum in the final state, in addition to the two electrons. Fig. 4(b), showing the diagram for neutrino-less double electron capture transitions, $0\nu e^-e^-$, will be discussed in Section 5.

There is a unique experimental signature of the neutrino-less double β^- decay, $0\nu\beta^-\beta^-$: the sum of the energies of the two correlated β^- electrons is constant and equal to the total decay energy. This gives a chance to distinguish the effect from that of the dominating $2\nu\beta^-\beta^-$ process, in which the energy is statistically shared among the four particles emitted. Typically, the $2\nu\beta^-\beta^-$ process is $10^3 \div 10^4$ times faster than the $0\nu\beta^-\beta^-$ one.

As mentioned above, the rate of the double beta decay offers a sensitive measure of the neutrino mass. This is so under the assumption that the neutrino mass diagram of Fig. 4 dominates the $0\nu\beta\beta$ decay. There exist, however, many additional, non-neutrino diagrams (Higgs, supersymmetry, right handed neutrinos *etc.*) which also can generate the $0\nu\beta\beta$ decay. In the following we assume that the contributions of these processes, if any, are negligible. What is worth stressing at this point is that while the exact value of the neutrino mass deduced from a successful $0\nu2\beta$ experiment can

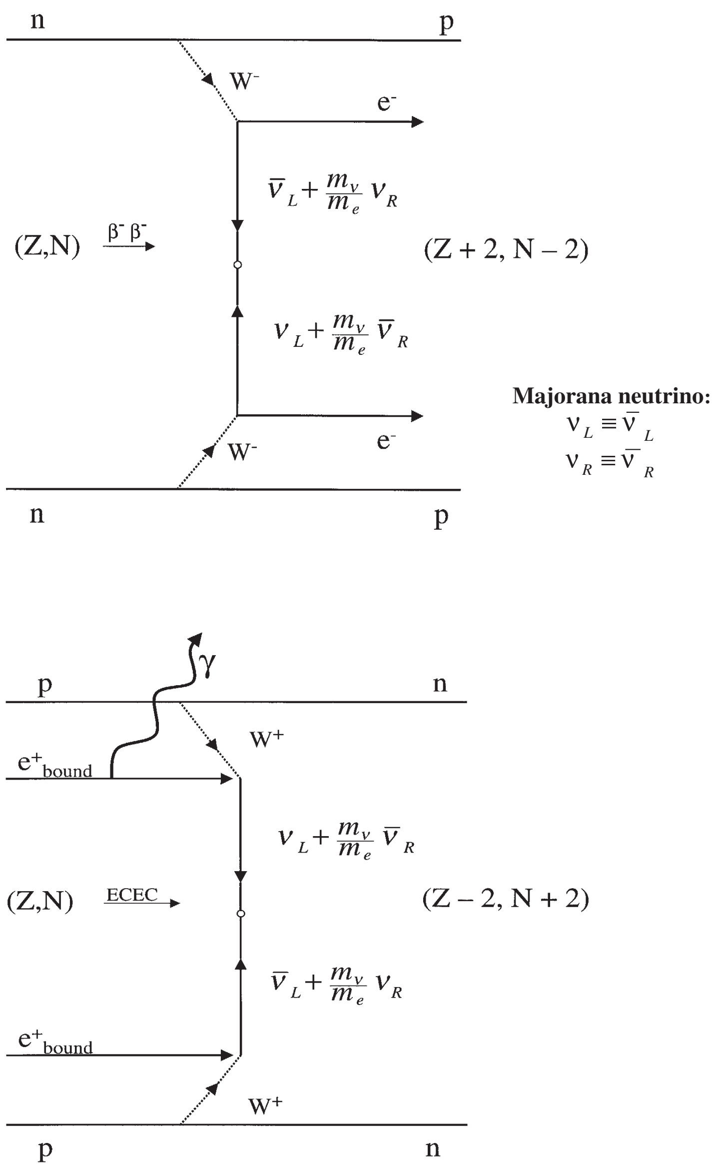

Fig. 4. Feynman diagram for neutrino-less double β^- decay (top) and for radiative neutrino-less double electron capture (bottom).

be subject to various corrections, the mere observation of the effect proves unambiguously the existence of a non-vanishing Majorana neutrino mass as well as the nonconservation of the lepton number. This remains true regardless of the mechanism causing the decay [13].

Crudely, the rate for the $0\nu\beta\beta$ processes can be factorised into the phase space factor, $G^{0\nu}(E,Z)$, and the nuclear matrix element, $M^{0\nu}$ (*cf. e.g.* [14]):

$$\Gamma(0\nu\beta\beta) = G^{0\nu}(E,Z)|M^{0\nu}(A,Z \to A, Z \pm 2)|^2\chi^2 \,. \tag{5}$$

The $G^{0\nu}$ factor contains the leptonic contributions including the final state electron wave functions. The crucial χ factor is the effective neutrino mass

$$\chi = \langle m^{\nu}_{\rm eff}\rangle = \sum_i |U_{ei}|^2 m_i^{\nu} e^{\delta}_{ei} \,, \tag{6}$$

where δ_{ei} are the Majorana phases, U_{ei} are the mixing amplitudes and the masses are in units of the electron mass, m_e.

The nuclear matrix element is a combination of the Gamov–Teller and Fermi terms:

$$M^{0\nu} = M^{0\nu}_{\rm GT} - \frac{g_V}{g_A} M^{0\nu}_{\rm F} \,. \tag{7}$$

From the oscillation experiments we can deduce the mixing angles and the mass square differences. The maximal and minimal values of m_ν are

$$\langle m^{\nu}\rangle_{\max} = \sum_i |U_{ei}|^2 m_i \,, \tag{8}$$

$$\langle m^{\nu}\rangle_{\min} = \max\left[(2|U_{ei}|^2 m_i - \langle m^{\nu}\rangle_{\max}, 0\right] . \tag{9}$$

The $\langle m^{\nu}\rangle$ value, to be eventually deduced from the double β decay, will fix the range of the neutrino masses!

The values of $M^{0\nu}$ for a large number of $\beta^-\beta^-$, $\beta^+\beta^+$ and β^+EC processes are calculated and/or reviewed in [15,16] and more recently in [4]. The straggling of these state-of-the-art values results occasionally in an order of magnitude differences in the life time expected. This reflects the uncertainties in the calculations. Extensive programmes of improving this situation are in progress [18]. The two basic approaches are the quasiparticle random phase approximation, QRPA, and the shell model, SM.

4. The experimental quest

The experiments searching for the $0\nu\beta^-\beta^-$ decay can be divided into two categories: the calorimetric experiments, in which the material of the source is usually identical with that of the detector, and the tracking experiments, in which the source and the detector are separate. The former automatically sums up the energies of the charged particles emitted. Large quantities of the material can be used. The main difficulty rests in suppressing the background. The only available means to do so are the shielding and the extreme purity of all the material of the detector housing and of the surrounding. The tracking detectors, counting the two electrons in coincidence, are somewhat less sensitive to the background. On the other hand, there are practical difficulties in using large amount of material, of the order of tons, in the form of thin sheets sandwiched between the detectors. The detectors in both kinds of experiment must fulfil the high resolution requirement. Otherwise the $0\nu\beta^-\beta^-$ peak in the sum spectrum will not be discernible from the dominating continuous physical background due to the $2\nu\beta^-\beta^-$ decay.

TABLE I

On-going and planned experiments for $0\nu\beta\beta$ decay.

PRESENT			FUTURE			
Isotope	$T^{0\nu}_{1/2}$ (y)	Ref.	Experiment	Ref.	Sensitivity to $T^{0\nu}_{1/2}$ (y)	Detector Description
^{48}Ca	$> 9.5 \times 10^{21}$	[25]	CANDLES	[26]	1×10^{26}	several tons of CaF_2 in liq. scint.
^{76} Ge	$> 1.9 \times 10^{25}$	[6]	GEM	[35]	7×10^{27}	1t ^{enr}Ge diodes in liq. N
	$> 1.6 \times 10^{25}$	[27]	GENIUS	[44]	1×10^{28}	1t 86% ^{enr}Ge diodes in liq. N
			Majorana	[45]	3×10^{27}	0.5t 86% segmented ^{enr}Ge diodes
^{82}Se	$> 2.7 \times 10^{22}$	[28]	–	–	–	–
^{100}Mo	$> 5.5 \times 10^{22}$	[29]	NEMO3	[46]	4×10^{24}	10kg of $\beta\beta(0\nu)$ isotopes (7kg Mo with tracking)
			MOON	[36]	1×10^{27}	34t ^{nat}Mo sheets between plastic scint.
^{116}Cd	$> 7 \times 10^{22}$	[30]	CAMEO	[37]	$> 10^{26}$	1t $CdWO_4$ crystals in liq. scint.
^{128}Te	$> 7.7 \times 10^{24}$	[31]	–	–	–	–
^{130}Te	$> 1.4 \times 10^{23}$	[32]	COBRA	[38]	1×10^{24}	10kg CdTe semiconductors
			CUORE	[47]	2×10^{26}	750kg TeO_2 bolometers
^{136}Xe	$> 4.4 \times 10^{23}$	[33]	EXO	[30]	8×10^{26}	1t ^{enr}Xe TPC (gas or liquid)
			Xe	[39]	5×10^{26}	1.56t of ^{enr}Xe in liq. scint.
			XMAS	[40]	3×10^{26}	10t of liq. Xe
^{150}Nd	$> 1.2 \times 10^{21}$	[34]	DCBA	[41]	2×10^{25}	20kg ^{enr}Nd layers tracking chambers
^{160}Gd			GSO	[42] [43]	2×10^{26}	2t Gd_2SiO_5:Ce crystal scint. in liq. scint.

A coincidence trigger suppressing the background can be provided by the 511 keV annihilation quanta in the case of $0\nu\beta^+\beta^+$ or $0\nu\beta^+EC$ decays. Likewise, decays to excited nuclear states can be observed in coincidence with the subsequent gamma rays. The practical limitation of these techniques rests in the very fast energy dependence of the phase space factor (roughly $\sim Q^5$, where Q is the available decay energy). This results in prohibitive enlargements of the lifetimes of the double β^+ decay progenitors.

Table I gives a list of the on-going and planned experiments searching for the $0\nu\beta\beta$ decay. Also given are the present and the eventually attainable life time limits.

The most accurate present limiting value has been obtained from the calorimetric measurement with 11 kg of ^{76}Ge material [6]. The superior stability and the high energy resolution of germanium detectors made of enriched ^{76}Ge permitted the authors to press the limiting life time value of ^{76}Ge down to 1.9×10^{25}y (90% CL) after a 53.9 kgy experiment. A particular statistical treatment of the same data has yielded the actual life time value of $T_{1/2} = 1.5 \times 10^{25}$y rather than a limit [19]. This treatment has been seriously criticised. The most recent analysis [20] goes beyond the criticism and combines the data of [6] and those of [21] to propose as the limiting value $T_{1/2}(^{76}\mathrm{Ge}) \geq 2.5(4.2) \times 10^{25}$y at 90 %(68%) CL. This corresponds to the limit for neutrino mass $m_\nu \leq 0.40$ eV assuming the nuclear matrix elements according to the calculation of [22].

5. Neutrino-less double electron capture — an overlooked possibility

The neutrino-less double electron capture decay without additional radiation violates the energy conservation. There has to be a medium to carry away the excess energy. This can be a single photon, two photons, an electron or some more exotic particle like a majoron. Such higher order processes are usually strongly retarded. They have, therefore, been discarded as a practical way to search for the neutrino-less transitions [48, 49]. It has recently been pointed out [50], however, that there may exist situations in which this retardation is compensated by favourable phase space relationships. In addition, the spectrometry with monoenergetic photons offers important experimental advantages.

The Feynman diagram for the process with emission of a single monoenergetic photon is shown in Fig. 4(b). The radiation is attributed to one of the captured electrons. In the spirit of Eq. (5) the rate for this process can be expressed as

$$\Gamma(0\nu ee) = G^{0\nu\gamma} \mid M^{0\nu}(A, Z \to A, Z-2) \mid^2 \left(\frac{m_\nu}{m_e}\right)^2 \mid M^\gamma \mid^2 \ . \qquad (10)$$

The photon emission probability estimated semi-classically is

$$| M^{\gamma} |^2 = \left(\frac{e^2}{2qm_e}\right) f\,, \tag{11}$$

where e is the electron charge, q is the photon momentum (it is equal to the mass difference less the binding energies of the two electrons) and f is a factor which describes the propagation of the radiating electron. Assuming the nuclear matrix elements for double electron capture and double β^- transitions as being equal, one can roughly compare the rates for the $0\nu\beta^-\beta^-$ and $0\nu ee\gamma$ processes. The retardation factor $R(\gamma)$ can be defined as the ratio of these rates:

$$R(\gamma) = \frac{\Gamma(0\nu ee\gamma)}{\Gamma(0\nu\beta^-\beta^-)} \simeq \left(\frac{m_e}{Q_{\beta\beta}}\right)^5 480\pi q\alpha^7 Z^6 f\,. \tag{12}$$

This strongly favours high Z nuclei with low decay energy as candidates for the neutrino-less double electron capture search. The structure of the f factor is complex. It favours low q values, particularly for electric dipole transitions. These correspond to cases where the electrons are captured respectively from the $1S$ and $2P$ states. Crudely, $f(el.dip.) \sim 1/q^4$. Note that the radiative capture of two $1S$ electrons is not allowed for nuclear transitions of the $0^+ \to 0^+$ type since the photon has to carry out at least one unit of angular momentum. Table II presents estimates given in [50] of the $(0\nu ee\gamma)$ process for a few selected nuclei. Very crude numbers taken for the nuclear matrix elements and the semi-classical, non-relativistic formulae used for the f factor result in one or even two orders of magnitude uncertainties. The life times given are those for $m_\nu = 1\,\mathrm{eV}$. They scale with $(m_\nu)^2$. The more accurate calculation [51] of f tends to yield larger lifetime values, corresponding to the upper limits of Table II. Even so, the estimates are highly encouraging, suggesting feasible experiments.

TABLE II

The relative enhancement factors and expected lifetimes.

Atom	abundance %	$Q(EC,EC)$ keV	$T_{1/2}(y),\ m_\nu = 1\,\mathrm{eV}$
$^{92}_{42}$Mo	15.84	1648.6	$10^{31\pm1}$
$^{108}_{48}$Cd	0.875	262	$10^{28\pm1}$
$^{180}_{74}$W	0.12	145	$2.5 \times 10^{25\pm2}$
$^{196}_{80}$Hg	0.146	820	$2 \times 10^{28\pm1}$

From the experimental point of view there are several advantages of the radiative electron capture process as compared to the double β^-emission:
• the monoenergetic photon escapes easily from fairly thick layers of the source material without energy degradation;
• the source can be separate from the detector;
• the physical background due to the competing $2\nu ee\gamma$ process is low;
• the photon emission is followed by that of the K X-ray.
The energy of these X-rays in heavy atoms such as W or Hg is of the order of 60–70 keV. This provides a precious coincidence trigger to combat the random background.

It is the last mentioned advantage which presumably is of the ultimate importance. To quote Ref. [4] "the history of double β experiments is the history of fighting the background". The calorimetric experiments for the $\beta^-\beta^-$ emitters have no trigger to select the wanted events from the overwhelming background radiation. Extreme purity of all the material is required. At this point it is worth stressing that in contrast to the $\beta^-\beta^-$ decay the phase space requirements for the $0\nu ee\gamma$ experiments favouring low q decays speak strongly for considering transitions leading to excited states in the final nucleus. These are followed by the discrete γ-ray emission providing yet another coincidence signature.

The experimental feasibility arguments have to include the decay rate and the cost estimates. Leaving the cost arguments aside and assuming 1 ton of the source material and the correspondingly larger amount of the high resolution detector (be it high purity Ge or a large bolometer) it seems to be feasible to design experiments for the 0ν double electron capture process in ^{180}W with the count rates of the order of $100 \times 10^{\pm 2}$ counts per year. The counting efficiency of about 10% has been assumed with the γ–K X-ray coincidence requirement to reduce the random background to a tolerable level. Prior to proper calculations of the nuclear matrix elements and the reduction of the present uncertainty factor, this estimate can be considered as encouraging.

6. Summary and outlook

There is a major challenge for the particle and nuclear physics community: to study the lepton sector, to determine the basic properties of one of the most important and certainly the least known unbound elementary particle: *the neutrino*, to make the next step beyond the Standard Model following the neutrino oscillation discovery. It is argued in this paper that the best chances to make such a major step are offered by studying the neutrino-less double beta decay. A successful result of such an endeavour would not only supply an accurate value of the effective electron neutrino mass and permit to fix the range of the neutrino masses. This effective neutrino mass would be the Majorana mass, proving unambiguously the Majorana nature of neutrino and the lepton number non-conservation at the same time.

There are several small and medium scale projects going and/or planned. The most ambitious proposals concern two double beta emitters: ^{76}Ge and ^{100}Mo. The recent suggestion of looking for the radiative double electron capture decay is at the early stage of assessment. More accurate rate and cost estimates and a realistic experimental design have to be made before embarking on the experiment. Still, the preliminary estimates are encouraging.

The significance of a successful double β decay search for our understanding of the lepton sector is difficult to overestimate. Yet, as mentioned above all the present projects can be classified as small or medium scale. There is a very suggestive plot of the "Moore's law od $0\nu\beta\beta$ decay" presented in Ref. [4]. This shows the exponential decrease with time of the limiting value for the effective neutrino mass measured in various experiments. The extrapolated line through the data reaches the minimum mass value deduced from the atmospheric neutrino oscillations around the year 2015. This is a rather pessimistic prediction considering how impatient our community has become recently, after the oscillation discovery. The wish to speed up this search, however, calls for a serious effort, financial and otherwise, at least on the scale of an average large accelerator experiment in particle physics.

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