The fun (?) of rare event searches

Kai Zuber
Institut für Kern- und Teilchenphysik, TU Dresden, 01069 Dresden, Germany
E-mail: zuber@physik.tu-dresden.de

Abstract. Various kinds of rare events can be studied but only a small fraction of these are mentioned in these proceedings. The search for rare events is quite some fun but also very hard work as typically very high backgrounds must be tackled for a very small signal. The first process discussed is double beta decay, which is an extremely rare process and requires half-live measurements around $10^{20}$ years for the neutrino accompanied mode, while for the neutrino-less mode much longer half-lives are already explored. Nuclear physics input is needed for the matrix elements and a quenching measurement of $g_A$ will be presented. In this case the focus is on the highly forbidden Cd-113 beta decay. New half-lives for the forbidden EC/beta decay measurement of V-50 will be presented. In addition new precision half-lives of long-living alpha decays will be presented as well.

1. Introduction

Neutrinos play a crucial role in modern particle, nuclear and astrophysics including cosmology [1, 2, 3]. It has been the major achievement of the last 20 years to show that neutrinos have a non-vanishing rest mass. The evidence arises from a deficit of upward going atmospheric muon neutrinos within the Super-Kamiokande experiment confirmed by long baseline accelerator experiments later and the solution of the solar neutrino problem by the SNO experiment being confirmed by nuclear reactor measurements. Both observations were awarded the Nobel price of physics 2015. All the mentioned observations can be explained by neutrino oscillations, which are depending on mass differences $\Delta m_{ij}^2 = m_j^2 - m_i^2$ with $i,j = 1, 2, 3$ as the three mass eigenstates. Furthermore, as we are dealing with a $3 \times 3$ unitary matrix, three more angles and one complex phase are involved. In case of neutrino-less double beta decay (see below) two more complex phases will appear. However, oscillation results do not provide absolute mass values. Hence, the determination of absolute neutrino masses is now a major issue. The classical way to search for a rest mass of the neutrino is the study of the endpoint region of electron spectra in beta decay (see [6] for a review). The KATRIN tritium experiment has started data taking recently. As beta decay measures the mass of $\bar{\nu}_e$ also activities have been started to use $\nu_e$. For that the endpoint of the internal bremsstrahlung of the EC of Ho-163 is investigated by the two experiments ECHO and HOLMES. Finally, further bounds on the total sum of neutrino masses can be obtained from cosmological studies, dominated by recent Planck satellite measurements combined with large scale structure information based on baryonic acoustic oscillations (BAO) suggesting that the summed mass of all three states is less than about 0.15 eV.
2. Double beta decay

Another laboratory process to search for neutrino masses is the rare nuclear decay of neutrinoless double beta decay

$$(Z, A) \rightarrow (Z + 2, A) + 2e^- \quad (0\nu\beta\beta\text{-decay})$$

(1)

accompanied by the Standard Model process of

$$(Z, A) \rightarrow (Z + 2, A) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta\text{-decay})$$

(2)

Single beta decay must be forbidden or at least strongly suppressed to observe this decay and only 35 potential double beta emitters exist in nature. As can be seen from Equation 1 the given decay mode is violating total lepton number by two units because the neutrino has to be its own anti-particle. If found this would be physics beyond the Standard Model. Being a decay the observable is a half-life which can be linked to the quantity of interest $\epsilon$ via

$$(T_{1/2}^{0\nu})^{-1} = G_{PS} |NME|^2 \epsilon^2$$

(3)

with $G_{PS}$ being the phase space, $|NME|$ as the involved nuclear matrix element for the physics process considered to describe this decay and $\epsilon$ the quantity of interest. Independent of the dominant decay mechanism, if $0\nu\beta\beta$-decay is ever observed experimentally it will imply that neutrinos are Majorana particles [7]. Furthermore, given all the possible processes it will become an important question what the individual contributions of the considered processes will be. For a recent review on the particle physics of double decay see [3, 8].

The standard interpretation considered is the one using light Majorana neutrino exchange. In this case $\epsilon$ is the effective Majorana neutrino mass $\langle m_{ee} \rangle$ given by

$$\epsilon = \langle m_{ee} \rangle = |\sum_i U_{ei}^2 m_i|$$

(4)

with $U_{ei}^2$ as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS)-mixing matrix elements [4, 5] containing the electron neutrino. The behaviour of $\langle m_{ee} \rangle$ as a function of the lightest mass eigenstate using the current oscillation results is shown in Figure 1. For $\langle m_{ee} \rangle$ values larger than about 100 meV neutrinos are almost degenerate, the inverted hierarchy covers a range between about 10-50 meV and below 10 meV is the region of the normal hierarchy. As can be seen, in the NH there is a chance for cancellation among the terms (Fig. 1). There is no such effect in the IH because of the non-maximal solar mixing angle $\theta_{12}$. Half-lives for the IH are in the region beyond $10^{26}$ years while half-lives in the NH are well beyond $10^{28}$ years.

Recently, a better understanding of the NME became a larger issue [9], and new experimental data have been accumulated to provide better input data for the theoretical calculations. This includes - among others - charge exchange reactions, muon capture, nucleon transfer reactions and the impact of deformation of nuclei in the transition.

2.1. General experimental considerations

Evidently measurements of half-lives around $10^{20}$ years and well beyond are by no means trivial. The signal for the $0\nu\beta\beta$-decay (see Equation 1) is a peak at the Q-value in the sum energy spectrum of the two electrons. From equation (1) it is also apparent that the maximal information obtainable from measurements will be the single electron energies, the opening angle between them and the daughter ion. This might be accompanied by characteristic gamma rays
Figure 1. A presentation of the effective Majorana neutrino mass \( \langle m_{ee} \rangle \) as a function of the lightest mass eigenstate. Shown are the inverted (green) and normal (red) hierarchy bands using the current values of the mixing angles and their 1\( \sigma \) and 3\( \sigma \) range. As can be seen within the normal hierarchy there can be perfect cancellation of terms in case that the lightest neutrino mass is in the range \( 10^{-3} - 10^{-2} \) eV (1\( \sigma \)) or even \( 10^{-4} - 10^{-2} \) eV (3\( \sigma \)).

in case of excited state transitions. The corresponding half-life in case of no background is given by the radioactive decay law (assuming a measuring time \( t \ll T_{1/2}^{\nu_{2}} \))

\[
T_{1/2}^{\nu_{2}} = \ln 2 m a N_{A} / N_{\beta\beta}
\]

with \( m \) the used mass, \( a \) the isotopic abundance of the double beta emitter, \( t \) the measuring time, \( N_{A} \) the Avogadro constant and \( N_{\beta\beta} \) the number of double beta events, which has to be taken from the experiment. If no peak is observed and a constant background (in general terms these are all potential energy depositions in the region of interest, i.e. around the Q-value, not being neutrino-less double beta decay) is assumed scaling linearly with time, a half-live estimate can be derived as

\[
(T_{1/2}^{\nu_{2}})^{-1} \propto a \times \epsilon \sqrt{M \times t / (B \times \Delta E)}
\]

where \( \epsilon \) is the efficiency for detection of the total energy of both electrons, \( \Delta E \) is the energy resolution at the peak position and \( B \) the background index normally given in counts/keV/kg/year. Hence, the most crucial parameters are a high detection efficiency and high abundance of the isotope of interest. This is the reason why almost all next generation experiments are using enriched materials and the "source = detector" approach, i.e. the emitter
is part of the detector itself. Furthermore, the energy resolution\(^1\) should be as good as possible to concentrate the few expected events in a small region and ideally the experiment should be background free. An irreducible background is the Standard Model process \(2\nu\beta\beta\)-decay. Here

Figure 2. Schematic plot of the sum energy spectrum for the two electrons in double beta decay. While the \(2\nu\beta\beta\)-decay shows a continuous energy distribution the \(0\nu\beta\beta\)-decay is producing a peak at the endpoint (Q-value). Various modes can be characterised by the phase space dependence (Q-E)\(^n\). The mode \(n=5\) is the \(2\nu\beta\beta\)-decay while the modes \(n=1,3,7\) involve the emission of a majoron, a Goldstone boson linked to the spontaneous breaking of lepton number. The different modes belong to different behaviours of the majoron with respect to weak isospin. The individual contributions are not to scale.

again energy resolution matters, because of the continuous spectrum of the \(2\nu\beta\beta\)-decay mode, its high energy part is leaking into the peak region. Nevertheless, this can be a worry as the half-life is typically several orders of magnitude shorter than the expected one for \(0\nu\beta\beta\)-decay.

2.2. Current status

As the decay rate for \(0\nu\beta\beta\)-decays scales with \(Q^5\) only isotopes with Q-values above 2 MeV are considered for experimental searches. They are listed together with their natural abundance and Q-value in Table (1). The current status with of lower half-limits with at least \(10^{25}\) years is given in Tab. 2.

As the current results point towards an upper limit of about 100 meV (given the NME uncertainties), the next goal will be to reach the region of the inverted hierarchy, i.e. \(\langle m_{ee} \rangle\) below \(\approx 50\) meV. The mentioned experiments plan upgrades (LEGEND, nEXO) and new experiments like SNO+ and others will add more data in the future.

2.3. Quenching of \(g_A\)

Recently, another quantity was brought to attention, namely the "quenching" of the axial-vector constant \(g_A\) which enters into Eq.3 with \(g_A^4\). Recent studies showed that this quenching can span a wide range [11]. It was suggested [12] that highly forbidden beta decays like Cd-113 should have some power to measure \(g_A\) as the spectral shape of the decay electrons is changing. This measurement has been done by the COBRA collaboration [13] which is running 64 CdZnTe

\(^1\) Care must be taken when comparing experiments, as for traditional reasons different detector technologies use either the Gaussian \(\sigma\) or the Full Width at Half Maximum \(\Delta E\) to quote energy resolution. The relation among the quantities is \(\Delta E = 2.35\sigma\).
Table 1. Table showing the eleven candidate isotopes with a Q-value larger than 2 MeV. Given are the natural abundances and Q-values as determined from precise Penning trap measurements or from the Atomic Mass Evaluation 2016 [10].

| Isotope | nat. abund. (%) | Q-value (keV) |
|---------|-----------------|---------------|
| $^{48}$Ca  | 0.187           | 4262.96 ± 0.84 |
| $^{76}$Ge  | 7.8             | 2039.006 ± 0.050 |
| $^{82}$Se  | 9.2             | 2997.9 ± 0.3 |
| $^{90}$Zr  | 2.8             | 3356.097 ± 0.086 |
| $^{100}$Mo | 9.6             | 3034.40 ± 0.17 |
| $^{110}$Pd | 11.72           | 2017.85 ± 0.64 |
| $^{116}$Cd | 7.5             | 2813.50 ± 0.13 |
| $^{124}$Sn | 5.64            | 2292.64 ± 0.39 |
| $^{130}$Te | 34.5            | 2527.518 ± 0.013 |
| $^{136}$Xe | 8.9             | 2457.83 ± 0.37 |
| $^{150}$Nd | 5.6             | 3371.38 ± 0.20 |

Table 2. Experimental lower half-live limits above $10^{25}$ years (as of end 2018) for the $0^{\nu}\beta\beta$-decay units of $10^{25}$ yrs. Also given are the name of the experiments and the selected isotope.

| Isotope | $T_{1/2}^{\text{exp.}}$ | Exp.   |
|---------|-----------------|--------|
| $^{130}$Te  | 1.5             | CUORE  |
| $^{136}$Xe  | 1.8             | EXO-200 |
| $^{76}$Ge  | 1.8             | MAJORANA |
| $^{76}$Ge  | 8               | GERDA  |
| $^{136}$Xe  | 10.7            | KL-Zen |

3. Alternative processes including positrons and electron capture

An equivalent process to the one discussed is $\beta^+\beta^+-\text{decay}$ also in combination with electron capture (EC). There are three different variants possible depending on the Q-value:

\[
(Z, A) \rightarrow (Z - 2, A) + 2e^+ (+2\nu_e) \quad (\beta^+\beta^+) \quad (7)
\]
\[
e^- + (Z, A) \rightarrow (Z - 2, A) + e^+ (+2\nu_e) \quad (\beta^+/EC) \quad (8)
\]
\[
2e^- + (Z, A) \rightarrow (Z - 2, A) (+2\nu_e) \quad (EC/EC) \quad (9)
\]

$\beta^+\beta^+$ is always accompanied by EC/EC or $\beta^+/EC$-decay. The positron production reduces the effective Q-value by $2m_e c^2$ per positron. Therefore, the rate for $\beta^+\beta^+$ is small and energetically only possible for six nuclides, however it would have a striking signature with four 511 keV gamma rays. It was shown that the $\beta^+/EC$-mode has an enhanced sensitivity to right-handed weak currents [15] and might be valuable to explore if $0^{\nu}\beta\beta$-decays discovered. The full Q-value is available in the $EC/EC$ mode which is the hardest to detect experimentally. However, it was proposed [16, 17] that if an excited state of the daughter nucleus is degenerate...
Figure 3. A plot of all best fit-values of $g_A$ as obtained from the measured Cd-113 spectra with the COBRA CdZnTe semiconductor detectors using various theoretical templates of different $g_A$. As each detector has enough statistics a histogram could be done. The three nuclear models used are the interacting shell model ISM (blue), the microscopic quasiparticle-phonon model (MQPM, red) and the Interacting boson fermion model (IBFM-2, black).

with the original ground state a resonance enhancement in the decay rate could occur and the de-excitation gammas would serve as a nice signal. Due to the sharpness of the resonance a more detailed study of candidates had to wait for Penning traps entering the field and exploring reasonable candidates. The most reliable one seems to be $^{152}$Gd (see Figure 4) where such a scenario is realised [18]. Despite this nice effect, to achieve the same sensitivity of $\langle m_{ee} \rangle$ as in $0\nu\beta\beta$-decays seems to require a measurement of the half-life an order of magnitude longer making this method slightly less attractive. Decays have been searched for in a number of isotopes with half-life limits ranging from $10^{15} - 10^{21}$ years, but no signal could be found in direct searches.

Figure 4. Compilation of enhancement factors in resonant neutrino-less double electron capture based on mass measurements with Penning traps (from [18]).

4. Other exemplaric measurements with new results of long-living decays
4.1. The decay of V-50
As Cd-113 has already been mentioned as a highly forbidden non-unique decay, another highly forbidden beta decay is V-50. Its decay scheme is shown in Fig. 5. A first measurement has
already been performed about 70 years ago and over time upper limits and positive observations are going hand in hand. A very clear first EC half-life measurement is reported in [19]. Theoretical calculations have been performed to predict the potential beta decay channel [20]. In a new, improved measurement using the LNGS ULB HPGe detector the EC-half life has been confirmed and the uncertainties reduced as well as an improvement by one order of magnitude in the beta decay channel [21]. The current values are now

\[
T_{1/2} > 1.9 \times 10^{19}\text{yrs (90\% C.I.) beta decay}
\]

\[
T_{1/2} = 2.67_{-0.18}^{+0.16} \times 10^{17}\text{yrs (68\% C.I.) EC decay}
\]

Figure 5. Left: Decay scheme of V-50, showing the EC and beta branches \((6^+ \rightarrow 2^+)\) and the corresponding \(\gamma\) energies. Right: Measured spectrum of a Vanadium sample for 240 days at the ULB HPGe detectors at LNGS. Clearly visible is the EC-line. Frustratingly, the Compton scattering of the EC-line causes a major background for a search of the V-50 beta decay line [21].

4.2. The \(\alpha\) decay of Sm-147 and Pt-190

With a newly built low background Frisch grid ionisation chamber [22] long living \(\alpha\)-decays can be explored. According to the Geiger-Nutall rule the region between 1-4 MeV is covering a variety of alpha emitters between \(10^6-17\) years. The background in the chamber in this region is only 1 event per 2 days. In a first measurement a comparison with the Sm-147 standard has been performed with very high statistics [23] and agrees very well with previous measurements, our precision is better than most of the Sm-measurements. After that Pt-190 has been measured which has a link to geo-chronometers. The abundance is only 0.02\% The according peak(s) can be seen in 6. The alpha-peaks are clearly well beyond the background. This measurement is the first ever which agrees with geochronological studies.

The established precise half-life measurements are [23, 24]

\[
T_{1/2} = 1.097(26) \times 10^{11}\text{years (Sm-147)}
\]

\[
T_{1/2} = (4.97 \pm 0.16) \times 10^{11}\text{years (Pt-190)}
\]

5. Summary

As much it is fun to search for rare events and very long-living isotopes it is also very hard work. In this proceeding the major issue was on neutrino-less double beta decay where now half-life limits around \(10^{26}\) years are studied. A study of highly forbidden beta decay of Cd-113 showed that the so called ”quenching of the axial-vector constant” indeed occurs as the
Figure 6. Left: The Sm-147 decay peak including background. The plot is showing 17 days of data from a longer measuring campaign. Right: A new measurement of Pt-190 of about 79 days. Notice the change in energy range in both plots, which is blown up for Pt-190.

measured value is significantly different from the normal value. Finally a decades long study of the V-50 half-life was improved again and touching theoretical calculations. Last but not least, also long-living $\alpha$-decays were presented, with improved precision which also adding to cosmo-chronometer dating.

[1] K. Zuber, *Neutrino physics*, CRC press 2012
[2] W. Rodejohann, *Int. Journal of Modern Physics* 20, 1833 (2011)
[3] H. Ejiri, J. Suohonon, K. Zuber, *Phys. Rep.* 797, 1 (2019)
[4] B. Pontecorvo, *Sov. Journal JETP* 7, 172 (1958)
[5] Z. Maki, M. Nakagawa and S Sakata, *Prog. Theo. Phys.* 28, 870 (1962)
[6] E. Otten, C. Weinheimer, *Rep. Prog. Phys.* 71, 086201 (2008)
[7] J. Schechter, J.W.F. Valle, *Phys. Rev. D* 23, 1666 (1981)
[8] M. J. Dolinski, A.W.P Poon, W. Rodejohann, arXiv:1902.04097, to published in Ann. Rev. Nucl. Part. Sci.
[9] K. Zuber, nucl-ex-0511009
[10] M. Wang et al., CPC 41, 1 (2016)
[11] F. F. Deppisch, J. Suohonon, *Phys. Rev. C* 94, 055501 (2016)
[12] J. Kostensalo, M. Haaranen, J. Suohonon, *Phys. Rev. C* 95, 044313 (2017)
[13] K. Zuber, *Phys. Lett. B* 519, 1 (2001)
[14] L. Bodenstein-Dresler et al., arXiv:1806.02254
[15] M. Hirsch et al., Z. Phys. A 347, 151 (1994)
[16] J. Berndtsb, A. DeRujula, C. Jarlskog, *Nucl. Phys. B* 223, 15 (1983)
[17] Z. Sujkowski, S. Wycech, *Phys. Rev. C* 70, 052501 (2004)
[18] S. Eliseev et al., *Phys. Rev. Lett.* 106, 052504 (2011)
[19] H. Dombrowski, S. Neumaier, K. Zuber, *Phys. Rev. C* 83, 054322 (2011)
[20] M. Haaranen, P. C. Srivastava, J. Suohonon, K. Zuber, *Phys. Rev. C* 90, 044314 (2014)
[21] M. Laubenstein, B. Lehnert, S. S. Nagorny, S. Nisi, K. Zuber, *Phys. Rev. C* 99, 045501 (2019)
[22] A. Hartmann et al., *Nucl. Instrum. Methods A* 814, 12 (2016)
[23] H. Wilsenach et al., *Phys. Rev. C* 75, 034618 (2017)
[24] M. Braun et al., *Phys. Lett. B* 768, 317 (2017)