Search for $\beta^+\text{EC}$ and ECEC processes in $^{74}\text{Se}$

A.S. Barabash $^1$ a, Ph. Hubert b, A. Nachab b, V. Umatov a

a Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russian Federation
b Centre d’Etudes Nucléaires, IN2P3-CNRS et Université de Bordeaux, 33170 Gradignan, France

Abstract

For the first time, limits on double-beta processes in $^{74}\text{Se}$ have been obtained using a $400 \text{ cm}^3$ HPGe detector and an external source consisting of natural selenium powder. At a confidence level of 90%, they are $1.9 \times 10^{18} \text{ y}$ for the $\beta^+\text{EC}(0\nu + 2\nu)$ transition to the ground state, $7.7 \times 10^{18} \text{ y}$ for the ECEC($2\nu$) transition to the $2^+_1$ excited state in $^{74}\text{Ge}$ (595.8 keV), $1.1 \times 10^{19} \text{ y}$ for the ECEC($0\nu$) transition to the $2^+_1$ excited state in $^{74}\text{Ge}$ (595.8 keV) and $5.5 \times 10^{18} \text{ y}$ for the ECEC($2\nu$) and ECEC($0\nu$) transitions to the $2^+_2$ excited state in $^{74}\text{Ge}$ (1204.2 keV). The last transition is discussed in association with a possible enhancement of the decay rate, in this case by several orders of magnitude, because the ECEC($0\nu$) process is nearly degenerate with an excited state in the daughter nuclide. Prospects for investigating such processes in future experiments are discussed.

PACS: 23.40.-s, 14.80.Mz

Key words: double-beta decay, double electron capture.

---

1 Corresponding author, Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia, e-mail: Alexander.Barabash@itep.ru, tel.: 007 (495) 129-94-68, fax: 007 (495) 127-08-33

Preprint submitted to Elsevier Science
1 Introduction

The experiments with solar, atmospheric, reactor and accelerator neutrinos have provided compelling evidences for the existence of neutrino oscillations driven by nonzero neutrino masses and neutrino mixing (see recent reviews [1,2,3] and reference therein). These results are impressive proof that neutrinos have a nonzero mass. However, the experiments studying neutrino oscillations are not sensitive to the nature of the neutrino mass (Dirac or Majorana) and provide no information on the absolute scale of the neutrino masses, since such experiments are sensitive only to the difference of the masses, $\Delta m^2$.

The detection and study of $0\nu\beta\beta$ decay may clarify the following problems of neutrino physics (see discussions in [4,5,6]): (i) neutrino nature: whether the neutrino is a Dirac or a Majorana particle, (ii) absolute neutrino mass scale (a measurement or a limit on $m_1$), (iii) the type of neutrino mass hierarchy (normal, inverted, or quasidegenerate), (iv) CP violation in the lepton sector (measurement of the Majorana CP-violating phases). Let us consider main modes of $\beta^-\beta^-$ decay:

\begin{align*}
(A, Z) &\rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu} & (1) \\
(A, Z) &\rightarrow (A, Z + 2) + 2e^- & (2)
\end{align*}

Process (1) is a second-order process, which is not forbidden by any conservation law. The detection of this process furnishes information about nuclear matrix elements (NME) for $2\beta$ transitions, which makes it possible to test the existing models for calculating these NMEs and contributes to obtaining deeper insight into the nuclear physics aspect of the double-beta decay problem. It is expected that the accumulation of experimental information about $2\nu\beta\beta$ processes will improve the quality of the calculations of NMEs, both for $2\nu$ and $0\nu$ decay. At the present time, $2\nu\beta\beta$ decay has so far been recorded for ten nuclei. In addition, the $2\nu\beta\beta$ decays of $^{100}$Mo and $^{150}$Nd to the first $0^+$ excited state of the daughter nuclides have been observed (see reviews [7,8]).

Process (2) violates the law of lepton-number conservation ($\Delta L = 2$) and requires that the Majorana neutrino has a nonzero rest mass or that an admixture of right-handed currents be present in weak interaction. In contrast to two-neutrino decay, neutrinoless double-beta decay has not yet been observed\(^2\) although, from the experimental point of view, it is easier to detect

\(^2\) The possible exception is the result with $^{76}$Ge, published by a fraction of the Heidelberg-Moscow Collaboration, $T_{1/2} \approx 1.2 \cdot 10^{25}$ y [9]. The Moscow portion of the Collaboration does not agree with this conclusion [10] and this result was subjected to criticism in other papers (see, for example, [11]). Thus at the present time this “positive” result is not accepted by the “$2\beta$ decay community” and it has to be
it. In this case, one seeks a peak in the experimental energy spectrum in the range of the double-beta transition energy with width determined by the detector’s resolution. Only limits on the level of $\sim 10^{24} - 10^{25}$ y for half-lives and $\sim 0.35 - 1.3$ eV for effective Majorana neutrino mass $\langle m_\nu \rangle$ have been obtained in the best modern experiments (see reviews [7,8]).

Much less attention has been given to the investigation of $2\beta^+, \beta^+\text{EC}$ and ECEC processes although such attempts were done from time to time in the past (see review [12]). Again, the main interest here is connected with neutrinoless decay:

$$\begin{align*}
(A, Z) &\rightarrow (A, Z - 2) + 2e^+ \\
e^- + (A, Z) &\rightarrow (A, Z - 2) + e^+ + X \\
e^- + e^- + (A, Z) &\rightarrow (A, Z - 2)^* \rightarrow (A, Z - 2) + \gamma + 2X
\end{align*}$$

Process (3) has a very nice signature because, in addition to two positrons, four annihilation 511 keV gamma quanta will be detected. On the other hand, the rate for this process should be much lower in comparison with $0\nu\beta\beta$ decay because of substantially lower kinetic energy available in such a transition (2.044 MeV is spent for creation of two positrons) and of the Coulomb barrier for positrons. There are only 6 candidates for this type of decay: $^{78}\text{Kr}$, $^{96}\text{Ru}$, $^{106}\text{Cd}$, $^{124}\text{Xe}$, $^{130}\text{Ba}$ and $^{136}\text{Ce}$. The half-lives of most prospective isotopes are estimated to be $\sim 10^{27} - 10^{28}$ y (for $\langle m_\nu \rangle = 1$ eV) [13]; this is approximately $10^3 - 10^4$ times higher than for $0\nu\beta\beta$ decay for such nuclei as $^{76}\text{Ge}$, $^{100}\text{Mo}$, $^{82}\text{Se}$ and $^{130}\text{Te}$ (see review [12]).

Process (4) has a nice signature (positron and two annihilation 511 keV gammas) and is not as strongly suppressed as $2\beta^+$ decay. In this case, half-life estimates for the best nuclei give $\sim 10^{26} - 10^{27}$ y (again for $\langle m_\nu \rangle = 1$ eV) [13].

In the last case (process (5)), the atom de-excites emitting two X-rays and the nucleus de-excites emitting one $\gamma$-ray (bremsstrahlung photon)\(^3\). For a transition to an excited state of the daughter nucleus, besides a bremsstrahlung photon, $\gamma$-rays are emitted from the decay of the excited state. Thus, in this case, we again have a very nice observational signature for this process. The rate is practically independent of decay energy and increases with both decreasing bremsstrahlung photon energy and increasing $Z$ [15,16]. The rate is checked by new experiments.

\(^3\) In fact processes with irradiation of inner conversion electron, $e^+e^-$ pair or two gammas are also possible [14] (in addition, see discussion in [15]). These possibilities are especially important in the case of ECEC($0\nu$) transition with capture of two electrons from K shell - in this case the transition with irradiation of one $\gamma$ is forbidden [14].
quite low even for heavy nuclei, with $T_{1/2} \sim 10^{28} - 10^{31}$ y [15]. Nevertheless, as was mentioned many years ago, a resonant process is possible if the mass of the daughter atom (in which electrons from the K (or L) shell are transformed into an excited state) coincides (within $< 1$ keV) with the mass of the initial atom in its ground state [17,18,19] 4. Possible rate enhancements on the order of $\sim 10^5 - 10^6$ may be obtained [15,19]. In Ref. [19], the resonant transition $^{112}\text{Sn}\rightarrow^{112}\text{Cd} (0^+; 1871$ keV) was investigated theoretically and the estimated half-life was $T_{1/2} \sim 3 \cdot 10^{24}$ y (for $\langle m_\nu \rangle = 1$ eV). Hence, the sensitivity of this process to the neutrino mass is comparable to the sensitivity of neutrinoless double-beta decay (see above). In Ref. [20], it is proposed to search for the $^{74}\text{Se}\rightarrow^{74}\text{Ge} (1204.2$ keV) resonant transition, the decay scheme of which is shown in Fig. 1. Taking into account that the atomic mass difference $\Delta M$ between $^{74}\text{Se}$ and $^{74}\text{Ge}$ is known to an accuracy of 2.3 keV (at one standard deviation), one can discuss possible resonant capture of two electrons from L shell for the transition to the 1204.2-keV level in $^{74}\text{Ge}$. In 66% of cases this process will be accompanied by a cascade of two $\gamma$-quanta of energies 608.4 and 595.8 keV; in 34% of cases it will be one $\gamma$-quantum of energy 1204.2 keV. It has to be mentioned that observation of these $\gamma$-quanta will provide extremely strong evidence of neutrinoless double-electron capture because two neutrino capture is heavily suppressed (because of the extremely low transition energy).

For completeness, let us present the two-neutrino modes of $2\beta^+, \beta^+\text{EC}$ and ECEC processes:

$$ (A, Z) \rightarrow (A, Z - 2) + 2e^+ + 2\nu \quad (6) $$

$$ e^- + (A, Z) \rightarrow (A, Z - 2) + e^+ + \nu + X \quad (7) $$

$$ e^- + e^- + (A, Z) \rightarrow (A, Z - 2) + 2\nu + 2X \quad (8) $$

These processes are not forbidden by any conservation laws, and their observation is interesting from the point of view of investigating nuclear-physics aspects of double-beta decay. Processes (6) and (7) are quite strongly suppressed because of low phase-space volume, and investigating process (8) is very difficult because one only has low energy X-rays to detect. In the case of double-electron capture, it is again interesting to search for transitions to the excited states of daughter nuclei [21], which are easier to detect from an experimental point of view.

A review of experimental investigations of $2\beta^+, \beta^+\text{EC}$ and ECEC processes is presented in [12]. It has to be mentioned here that a "positive" result was obtained in Ref. [15], the resonance condition for transitions with a bremsstrahlung photon is $E_{\text{brems}} = Q_{\text{res}} = | E(1S, Z - 2) - E(2P, Z - 2) |$, i.e. when the photon energy becomes comparable to the $2P - 1S$ atomic level difference in the final atom.

4 In Ref. [15], the resonance condition for transitions with a bremsstrahlung photon is $E_{\text{brems}} = Q_{\text{res}} = | E(1S, Z - 2) - E(2P, Z - 2) |$, i.e. when the photon energy becomes comparable to the $2P - 1S$ atomic level difference in the final atom.
Fig. 1. Energetics of the $^{74}$Se $0\nu$ECEC decay indicating the near degeneracy of the $^{74}$Se ground state and the second excited state in $^{74}$Ge. The circle marks the part magnified in the lower part of the figure.

obtained in a geochemical experiment with $^{130}$Ba where the ECEC$(2\nu)$ process was detected with a half-life of $(2.2 \pm 0.5) \cdot 10^{21}$ y [22].

The present work is dedicated to search for different modes of $\beta^+EC$ and ECEC processes in $^{74}$Se.

2 Experimental

The experiment has been performed in the Modane Underground Laboratory (depth of 4800 m w.e.). The natural selenium powder sample was measured using a 400 cm$^3$ low-background HPGe detector.

The Ge spectrometer was composed of p-type crystals. For the HPGe detector the cryostat, the endcap and the main mechanical parts were made of very pure Al-Si alloy. The cryostat had a J-type geometry to shield the crystal from radioactive impurities in the dewar. The passive shielding consisted of 4 cm of Roman-era lead and 3-10 cm of OFHC copper inside 15 cm of ordinary lead. To remove $^{222}$Rn gas, one of the main sources of the background, a special
effort was made to minimize the free space near the detector. In addition, the passive shielding was enclosed in an aluminum box flushed with high-purity nitrogen.

The electronics consisted of currently available spectrometric amplifiers and a 8192 channel ADC. The energy calibration was adjusted to cover the energy range from 50 keV to 3.5 MeV, and the energy resolution was 2.0 keV for the 1332-keV line of $^{60}$Co. The electronics were stable during the experiment due to the constant conditions in the laboratory (temperature of $\approx 23^\circ$ C, hygrometric degree of $\approx 50\%$). A daily check on the apparatus assured that the counting rate was statistically constant.

The sample of natural selenium powder was placed in a circular plastic box and put on the endcap of the HPGe detector. The mass of the powder was 563 g, 4.69 g of which was $^{74}$Se (as the natural abundance is 0.89%). The duration of measurement was 436.56 hours.

A search for different $\beta^+\text{EC}$ and ECEC processes in $^{74}$Se was carried out using the germanium detector to look for $\gamma$-ray lines corresponding to these processes. Hereinafter, $Q'$ is the effective $Q$-value defined as $Q' = \Delta M - \epsilon_1 - \epsilon_2$ where $\Delta M$ is the difference of parent and daughter atomic masses, $\epsilon_i$ is an electron binding energy in a daughter nuclide.

The ECEC(0$\nu$) transitions were considered for three cases of electron captures as is shown in Fig. 1.

First, two electrons are captured from the L shell. In this case, $Q'$ is equal to $\sim 1206.9$ keV and three transitions are investigated, i.e.

1) to the second $2^+$ level of $^{74}$Ge (1204.2 keV), accompanied by 595.8 keV and 608.4 keV de-excitation $\gamma$-quanta (66%), or a 1204.2 keV de-excitation $\gamma$-quantum (34%);

2) to the first $2^+$ level of $^{74}$Ge (595.8 keV), accompanied by a 611.1 keV bremsstrahlung $\gamma$-quantum and a 595.8 keV de-excitation $\gamma$-quantum;

3) to the ground state of $^{74}$Ge, accompanied by a 1206.9 keV bremsstrahlung $\gamma$-quantum.

Second, one electron is captured from the K shell, another from the L shell. In this case, $Q'$ is equal to $\sim 1197.2$ keV and two transitions are investigated, i.e.

1) to the first $2^+$ level of $^{74}$Ge, accompanied by a 601.4 keV bremsstrahlung $\gamma$-quantum and a 595.8 keV de-excitation $\gamma$-quantum;

2) to the ground state of $^{74}$Ge, accompanied by a 1197.2 keV bremsstrahlung $\gamma$-quantum.

Third, two electrons are captured from the K shell. In this case, $Q'$ is equal to $\sim 1185.9$ keV and two transitions are investigated, i.e.

1) to the first $2^+$ level of $^{74}$Ge, accompanied by a 590.1 keV bremsstrahlung $\gamma$-quantum and a 595.8 keV de-excitation $\gamma$-quantum;
2) to the ground state of $^{74}$Ge, accompanied by a 1185.9 keV bremsstrahlung $\gamma$-quantum.

The $\beta^+\text{EC}(0\nu+2\nu)$ transition is possible only to the ground state of $^{74}$Ge, accompanied by one positron which gives two annihilation $\gamma$-quanta. The modes of $(0\nu$ and $2\nu$) aren’t distinguished with our technique.

The usual EEC(2$\nu$) transitions, accompanied by detectable $\gamma$-rays, are

1) the transition to the second $2^+$ level of $^{74}$Ge with the $\gamma$-rays, 595.8 keV (66%), 608.4 keV (66%) and 1204.2 keV (34%),

2) the transition to the first $2^+$ level of $^{74}$Ge with one de-excitation $\gamma$-quanta, 595.8 keV.

The partial gamma-ray spectra in the energy ranges corresponding to the different decay modes of $^{74}$Se are shown in Fig. 2 together with the background (without Se powder) spectrum reduced to the measuring time of the experiment. In the Fig. 2 all visible peaks in experimental and background spectra are within one sigma error, i.e. they are background peaks. No extra events that are statistically significant, i.e. more than $3\sigma$ over background, are observed for the investigated energies.

The Bayesian approach [23] was used to estimate limits on transitions of $^{74}$Se to the ground and excited states of $^{74}$Ge. To construct likelihood functions every bin of the spectrum is supposed to have a Poisson distribution with its mean $\mu_i$ and the number of events equal to the content of this $i$th bin. The mean $\mu_i$ can be written in general form as

$$\mu_i = N \sum_m \varepsilon_m a_{mi} + \sum_k P_k a_{ki} + b_i$$

The first term in (9) describes the contribution of the investigated process that may have a few $\gamma$-lines contributing appreciably to the $i$th bin; the parameter $N$ is the number of decays, $\varepsilon_m$ is the detection efficiency of the $m$th $\gamma$-line of this transition and $a_{mi}$ is the contribution of $m$th line to the $i$th bin. For low-background measurements a $\gamma$-line may be taken to have a gaussian shape. The second term gives contributions of background $\gamma$-lines; here $P_k$ is the area of the $k$th $\gamma$-line and $a_{ki}$ is its contribution to the $i$th bin. The third term represent the so-called “continuous background” $b_i$ which has been selected as a straight-line fit after rejecting all peaks in the region of interest. We have selected this region as the peak investigated $\pm 30$ standard deviations ($\approx 20$ keV). The likelihood function is the product of probabilities for selected bins. Normalizing this to 1 over parameter $N$, it becomes the probability density function for $N$, which is used to calculate limits for $N$. To take into account errors of $\gamma$-line shape parameters, peak areas, and other factors, one
Fig. 2. Energy spectra with natural Se and without Se (background) in the ranges of investigated $\gamma$-rays.
should multiply the likelihood function by the error probability distributions for those values, and integrate on those, providing the averaging probability density function for $N$.

In our case, we have taken into consideration only errors of peak areas for the 511-keV annihilation peak and for the 609.3-keV gamma-line from $^{214}$Bi, supposing other errors are negligible. Limits have been calculated for different combinations of $\gamma$-lines corresponding to the transitions under study. The best results are given in Table 1.

The photon detection efficiency for each investigated process has been computed with the CERN Monte Carlo code GEANT3.21. Special calibration measurements with radioactive sources and powders containing well-known $^{226}$Ra activities confirmed that the accuracy of these efficiencies is about 10%.

3 Discussion

The obtained results are presented in Table 1. It is necessary to stress that $^{74}$Se has never been investigated before and all results presented here are obtained for the first time. Neither has this isotope been investigated theoretically; thus, there are no predictions with which to compare. Nevertheless, we will try to estimate the significance of the obtained results and the possibility to increase the sensitivity of this type of experiments in the future.

It is clear that $^{74}$Se is not a very good candidate to search for $\beta^+EC(2\nu)$ and EEC(2\nu) processes and chance of detecting these decays is very small (even taking into account a possible increase in sensitivity: see below). Nevertheless, the obtained experimental limits are quite interesting as they prohibit some unexpected (exotic) processes.

Concerning the EEE(0\nu) processes, the main hope is to observe a resonant transition to the 1204.2-keV excited state of $^{74}$Ge. In fact, the experimental spectrum has some excess of events in the ranges of 595.9 keV (1.8 $\sigma$). Most probably that this excess of events is connected with cosmogenic isotope $^{74}$As ($T_{1/2} = 17.8$ d). This isotopes is produced on the surface in reaction $^{74}$Se(n,p)$^{74}$As. Fortunately half-life of this isotope is quite short and it can not be a serious background for future underground experiments (one just has to wait a few months before starting the measurement).

It would therefore be better to investigate a larger quantity of $^{74}$Se for a longer time. Further, it is necessary to precisely determine the $\Delta M$ value for $^{74}$Se and $^{74}$Ge; this is a realistic task (in Ref. [20], the possibility of measurements with an accuracy $\sim$ 200 eV is discussed). A theoretical investigation of this
Table 1
The limits on double-beta processes in $^{74}$Se. The second column presents $\gamma$-ray energies in keV and their efficiencies used to estimate half-lives. Limits on half-lives $T_{1/2}$ are given at a confidence level of 90%. *) For transition with irradiation of $e^+e^-$ pair - see footnote 3). **) This transition is forbidden and the limit is presented here just for comparison.

| Transitions | $\gamma$-ray (efficiency) | $T_{1/2}, 10^{19}$ y |
|-------------|--------------------------|----------------------|
| $L_1^1L_2^2, Q' = 1206.9$ keV, ECEC($0\nu$) to the $2^+_2$ (1204.2-keV) level of $^{74}$Ge | 595.8 keV (1.88%) | 0.55 |
| $L_1^1L_2^2, Q' = 1206.9$ keV, ECEC($0\nu$) to the $2^+_1$ (595.8-keV) level of $^{74}$Ge | 611.1 keV (2.70%) | 1.30 |
| $L_1^1L_2^2, Q' = 1206.9$ keV, ECEC($0\nu$) to the ground state of $^{74}$Ge | 1206.9 keV (2.13%) | 0.41 |
| $K_1^1L_2^2, Q' = 1197.2$ keV, ECEC($0\nu$) to the $2^+_1$ (595.8-keV) level of $^{74}$Ge | 601.4 keV (2.71%) | 1.12 |
| $K_1^1K_2^2, Q' = 1185.9$ keV, ECEC($0\nu$) to the ground state of $^{74}$Ge | 1185.9 keV (2.15%) | 0.62 |
| $\beta^+EC(0\nu + 2\nu)$ transition to the ground state of $^{74}$Ge | 511 keV (6.74%) | 0.19 |
| ECEC($2\nu$) to the $2^+_1$ (1204.2-keV) level of $^{74}$Ge | 595.8 keV (1.88%) | 0.55 |
| ECEC($2\nu$) to the $2^+_1$ (595.8-keV) level of $^{74}$Ge | 595.8 keV (3.13%) | 0.77 |

transition and an estimate of the rate of ECEC($0\nu$) process for different channels are needed. Experimental possibilities are as follows:

1) With 1 kg of enriched $^{74}$Se in the setup described in the preceding section, the sensitivity after one year of measurement will be $3 \cdot 10^{21}$ y.

2) To use $\gamma-\gamma$ coincidence technique that uses two HPGe detectors to observe cascade of the two $\gamma$ rays (595.8 keV and 608.4 keV). Using detector described in [24] with 1 kg of enriched $^{74}$Se and after one year of measurement sensitivity...
will be on the level \( \sim 3 \cdot 10^{21} \) y.

3) With 200 kg of enriched \(^{74}\)Se using an installation such as GERDA [25] or MAJORANA [26,27] (where 500 kg of low-background HPGe detectors are planned to be used), the sensitivity after 10 years of measurement may reach \( \sim 10^{26} \) y.

4) To use TGV type detector [28] which can reach sensitivity \( \sim 10^{20} \) y with 10 g of \(^{74}\)Se for one year of measurement.

It is emphasized that these types of measurements can be done with some other isotopes as well. In Table 2, the most interesting of such isotopes are presented along with some relevant properties. One of the most promising candidates is \(^{112}\)Sn.

**Table 2**

The prospective isotopes. Here A is isotopic abundance, \( \Delta M \) is the atomic mass difference in keV of parent and daughter nuclei, \( E^* \) is the energy in keV of a candidate excited state of the daughter nuclide (with its spin and parity in parenthesis) for a resonant transition, and \( E_K, E_{L1}, E_{L2}, E_{L3} \) are the energies of K, L1, L2, and L3 shells of a daughter nuclide in keV.

| Nuclei | A, %  | \( \Delta M \)       | \( E^* \)    | \( E_K \) | \( E_{L1} \) | \( E_{L2} \) | \( E_{L3} \) |
|--------|------|----------------------|-------------|----------|-------------|-------------|-------------|
| \(^{74}\)Se | 0.89 | 1209.7 \pm 2.3       | 1204.2(2^+) | 11.10    | 1.41        | 1.23        | 1.22        |
| \(^{78}\)Kr | 0.35 | 2846.4 \pm 2.0       | 2838.9(2^+) | 12.66    | 1.65        | 1.47        | 1.43        |
| \(^{96}\)Ru | 5.52 | 2718.5 \pm 8.2       | 2700(?)     | 20       | 2.86        | 2.62        | 2.52        |
| \(^{106}\)Cd | 1.25 | 2770 \pm 7.2         | 2741.0(1, 2^+) | 24.35 | 3.60        | 3.33        | 3.17        |
| \(^{112}\)Sn | 0.97 | 1919.5 \pm 4.8       | 1871.0(0^+) | 26.71    | 4.02        | 3.73        | 3.54        |
| \(^{130}\)Ba | 0.11 | 2617.1 \pm 2.0       | 2608.42(?)  | 34.56    | 5.44        | 5.10        | 4.78        |
| \(^{136}\)Ce | 0.20 | 2418.9 \pm 13        | 2399.87(1^+, 2^+) | 37.44 | 5.98        | 5.62        | 5.25        |
| \(^{162}\)Er | 0.14 | 1843.8 \pm 5.6       | 1745.71(1^+) | 53.79    | 9.05        | 8.58        | 7.79        |

4 Conclusion

For the first time, limits on double-beta processes in \(^{74}\)Se have been obtained. Some other prospective isotopes where the resonance mechanism can be realized are presented. It is demonstrated both that, in future larger-scale experiments, the sensitivity to ECEC(0\(\nu\)) processes for such isotopes can be on the order of \(10^{26} \) y and that, under resonant conditions, this decay will be competitive with 0\(\nu/\beta\beta\) decay.
Acknowledgement

The authors would like to thank the Modane Underground Laboratory staff for their technical assistance in running the experiment. We are very thankful to Dr. V. Tretyak for his useful remarks. Portions of this work were supported by a grant from INTAS (no 03051-3431).

References

[1] J.W.F. Valle, hep-ph/0608101
[2] S.M. Bilenky, hep-ph/0607317
[3] R.N. Mohapatra and A.Y. Smirnov, hep-ph/0603118
[4] S. Pascoli, S.T. Petcov and W. Rodejohann, Phys. Lett. B 558 (2003) 141.
[5] R.N. Mohapatra et al., hep-ph/0510213
[6] S. Pascoli, S.T. Petcov and T. Schwetz, Nucl. Phys. B 734 (2006) 24.
[7] A.S. Barabash, JINST 1 (2006) P07002; hep-ex/0602037
[8] A.S. Barabash, hep-ex/0608054
[9] H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198.
[10] A.M. Bakalyarov et al., Phys. Part. Nucl. Lett. 2 (2005) 77; hep-ex/0309016
[11] A. Strumia and F. Vissani F., Nucl. Phys. B 726 (2005) 294.
[12] A.S. Barabash, Phys. At. Nucl. 67 (2004) 438.
[13] M. Hirsch et al., Z. Phys. A 347 (1994) 151.
[14] M. Doi and T. Kotani, Prog. Theor. Phys. 89 (1993) 139.
[15] Z. Sujkowski and S. Wycech, Phys. Rev. C 70 (2004) 052501(R).
[16] D. Vergados, Nucl.Phys. B 218 (1983) 109.
[17] R.G. Winter, Phys. Rev. 100 (1955) 142.
[18] M.V. Voloshin, G.V. Mitselmakher and R.A. Eramzhyan, JETP Lett. 35 (1982) 656.
[19] J. Bernabeu, A. De Rujula and C. Jarlskog, Nucl. Phys. B 223 (1983) 15.

[20] D. Frekers, [hep-ex/0506002]

[21] A.S. Barabash, JETP Lett. 59 (1994) 644

[22] A.P. Meshik et al., Phys. Rev. C 64 (2001) 035205.

[23] Review of Particle Physics, Phys. Lett. B 592 (2004) 283.

[24] L. De Braeckeler, M. Hornish, A. Barabash and V. Umatov, Phys. Rev. Lett. 86 (2001) 3510.

[25] I. Abt et al., [hep-ex/0404039]

[26] Majorana White Paper, [nucl-ex/0311013]

[27] C.E. Aalseth et al., Nucl. Phys. B (Proc. Suppl.) 138 (2005) 217.

[28] I. Stekl et al., Czech. J. Phys. 56 (2006) 505.