RESULTS OF A SEARCH FOR THE NEUTRINOLESS DOUBLE BETA DECAY OF ^{76}Ge TO THE FIRST EXCITED STATE OF ^{76}Se

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ABSTRACT

A search for the neutrinoless double beta decay of ^{76}Ge to the first excited state $J^{\pi}=2^+_1$, E=559.1 KeV of ^{76}Se has been carried out in the Frejus tunnel using a coincidence technique between Ge and NaI detectors. No peak has been observed in the electron energy spectrum at the $Q_{2\beta}(0^+\rightarrow 2^+)$ value of 1482 KeV. That implies a half-life lower limit of $T^{0\nu}_{1/2}(0^+\rightarrow 2^+) \geq 6 \times 10^{22}$ years. However the experimental data display a coincidence, at the level of 2.5σ, between an energy deposition of 1483.7±0.5 KeV in the Ge detector and 558±15 KeV in the NaI detector. The main features of such a coincidence effect are analyzed and, in spite of its small statistical significance, its possible interpretation is discussed.

1.INTRODUCTION

The nuclear beta decay without emission of neutrinos has attracted since long time a considerable attention as a test of lepton number conservation and as a low-energy laboratory to study the nature and properties of the neutrino. Favoured by phase space with respect to the conventional two neutrino decay, it needs to break the lepton number conservation law and the γ_5-invariance of the weak current to occur. For this to happen the neutrino field must be self-conjugate (Majorana neutrino), and should have a non-zero mass or a right handed admixture, or both. The double beta decay takes place mainly between the 0^+ ground states of the father and daughter nuclei. In some cases (as in the ^{76}Ge) transitions to excited states of the daughter nucleus are also energetically allowed. These transitions are, however, inhibited by phase space in comparison with the transition to the ground state. The neutrinoless $0^+ \rightarrow 0^+$ decays go only through the 2n-mechanism and can be induced by a non-zero Majorana mass ($<m_\nu>$) or a left-right (handed) interference in the virtual neutrino exchange ($<\lambda>$,$<\eta>$), or both. However the neutrinoless transition to the 2^+ excited state can only be produced by the presence of a right handed admixture (and can go through the 2n and Δ-resonance mechanisms). That makes these transitions appealing for searching right handed currents in spite of its expected smallness.

We report in this paper, the results of a search for the neutrinoless double beta decay of ^{76}Ge(0^+) to the first, 2^+, excited state of ^{76}Se, at 559.1 KeV ($Q_{0\text{-}2}$ = 1482 KeV), in a Ge/NaI coincidence experiment carried out at the Frejus Tunnel. Many experiments have been devoted to a direct search of the double beta decay of the ^{76}Ge since the pioneering work of the Milano group[1)], but no double beta signal has been reported up to now.

2. THE 2ß / γ COINCIDENCE EXPERIMENT

The Frejus experiment is a search of the 2ß neutrinoless transition ^{76}Ge(0^+)$\rightarrow$^{76}Se(2^+) + 2 e^-, which looks for a coincidence between the two-electron signal at $E_{2\beta}$ = 1482 KeV and the deexcitation photon ^{76}Se(2^+)$\rightarrow$^{76}Se(0^+) + γ at E_γ = 559.1 KeV in the Ge coincidence spectrum gated by a NaI window around 560 KeV. The electron signal is registered in a set of 4-Ge detectors and the photon signal is registered in a 4π-array of 19 NaI detectors surrounding the germanium set. The details of the experimental set up and procedure, as well as some preliminary results have been published elsewhere[2)]. Now we present the final results after 6122 hours of active counting time. The main parameters of the experiment are: The overall energy resolution of the summed 4-Ge spectra (after 6122 hours) is -with gain correction- $\Gamma(1482)$ = 2.4 KeV and $\Gamma(2040)$ = 2.7 KeV (2040.7 KeV is the Q value of the $0^+ \rightarrow 0^+$ transition). The data were recorded every ~ 250 h, and then combined taking properly into account slight gain shifts -software stabilization-. The overall energy resolution of the 19 NaI after 6122 hours is $\Gamma(560)$ ~ 11 % = 62 KeV. The efficiency of our detector assembly has been computed by a Monte Carlo simulation which uses the EGS4 code implemented with the GEOM software[3)] developed for dealing with complex geometries. The (averaged) overall efficiency (escape probability times fully absorption probability), for the 559.1 photons coming from the 4-Ge detector to be totally absorbed in the NaI enceinte is $\varepsilon = 0.23$. Our code program has been successfully checked with various experimental results[3]. The fiducial volume V_f of the 4Ge assembly has been computed also by Monte Cârlo simulation by using the EGS4 code. The value obtained is $V_f(0^+ \to 2^+)=403$ cm^3. As far as the background is concerned we got B=(0.35±0.03) counts/KeV.y.10^{23} at about 1482 KeV in the coincidence spectra (i.e. 2.25 c/KeV x Kg x y). Putting all the experimental parameters together, the expected sensitivity of our detector system is, for t=6122 hours, S = 5.4 x 10^{22} years.

The Ge spectrum recorded in coincidence with the 559.1 KeV photons, registered by the NaI enceinte, was gated by a NaI window of ± 30.7 KeV (2.35σ). The choice of the window has been done by optimizing the signal to noise ratio. That happens in a region which ranges from about 2.35σ up to, about, 2.80σ. As the analysis in other current experiments has been done[4] for 2.35σ we have chosen this value for sake of comparisons. Figure (1) shows a close up of the coincidence spectrum in the energy region 1450 KeV to 1500 KeV, which contains the zone where the double beta signal would be expected. According to the commonly used value[5] of the transition energy $Q_{2\beta} = 2040.7 \pm 0.5$ (or to the more recent one[5]), $Q_{2\beta} = 2041.4 \pm 0.5$ KeV , the peak (if any) in the coincidence spectrum should appear at $E = Q_{2\beta} - 559.1 = 1481.6$ KeV (or 1482.3 KeV), say 1482 KeV. No peak appear at this energy, and only a lower limit of the half-life can be given. A maximum likelihood estimate provides the lower limit $T_{1/2}^{0\nu}(0^+ \to 2^+)_{1482\ KeV} \geq 6 \times 10^{22}$ years at 68 % c.l..

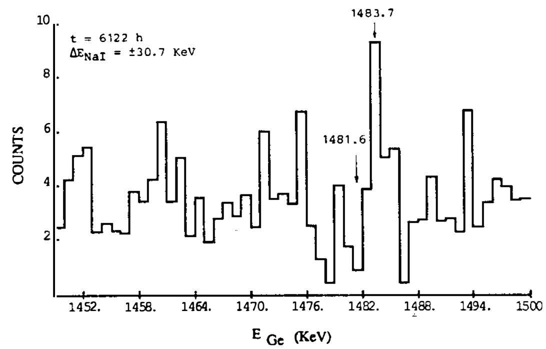

Fig (1): Close up of the Ge coincidence spectrum in the $0^+ \to 2^+$ energy region

However, as can be seen in Fig (1), a small accumulation of counts (at the level of 2.5σ), appears in such a coincidence spectrum, at an energy of E_{Ge} = 1483.7 KeV. Faced to this accumulation, which -in spite of its small statistical significance- might induce to think in a neutrinoless double beta effect, we shall analyze in the following the main features of such a coincidence effect trying to gather arguments in favour or disfavour of such a possibility.

Let us see first whether it is really a peak. In the spectrum given in Fig (1), the ΔE = 3 KeV (2.9σ) energy bin from 1482 KeV to 1485 KeV contains 18 counts. In the 35 KeV interval from 1466 KeV to 1501 KeV there is a total of 122 counts. The mean flat background is B = (3.4 ± 0.4) c/KeV. A binomial analysis gives a probability 0.8 % to have the 122 events distributed as in Fig (1) if they were actually due to a random background. In fact, a standard maximum likelihood method gives to such a peak (taking into account the chosen energy bin) an area of S = 13.3 ± 5.3 counts in 6122 hours over a background of B = (5.5 ± 0.6) x 10^{-4} c / KeV x h. The centroid is located at E_{Ge} = 1483.7 ± 0.5 KeV. The same analysis has been carried out with different NaI windows, getting essentially the same result. From the NaI/Ge chart of coincidence events, a bidimensional likelihood procedure has been performed, and it has been found that there exists, indeed, a peak located at E_{Ge} = 1483.9 ± 0.4 KeV cross E_{NaI} = 558 ± 15 KeV, with an area of S = 12.6 ± 5.7 counts over a background of $B_{NaI \times Ge} = 8.6 \times 10^{-5}$ counts / 10 KeV x 1 KeV x 1 h (probability of no peak hypothesis: 1.3 %). This result which does not depend on any, a priori, selected NaI window, is in good agreement with the previous one and determines the energy position of the coincidence effect.

There exists a noticeable feature of the Ge spectrum which strength the conclusion that the 1483.7 KeV electron peak is really in coincidence with a photon of 560 KeV. In the Ge coincidence spectra obtained for different positions of the NaI window, it is seen that the 1483.7 KeV peak decreases when the position is shifted away from the 560 KeV value. Alternatively if one draws the intensity of the coincidence lines versus the NaI energy, it is seen that the intensity gaussian curve corresponding to the 1483.7 accumulation is in coincidence with 557 ± 9 KeV in agreement with the previous determinations. By means of this procedure it has been checked that only the 1483.7 KeV peak of the main Ge coincidence spectrum, is centered around 560 KeV.

The question of the compatibility of the peak energy with the $Q_{2\beta}$ value relies, heavily, on the accuracy of the corresponding mass doublets measurements. Although the commonly used value is that of Ellis et al[5], $Q_{2\beta}(0\text{-}2)$ = 1481.6 ± 0.5 KeV, the new[5] (more complete) result of these authors, would imply $Q_{2\beta}(0\text{-}2)$ = 1482.3 ± 0.5 KeV, which compares fairly well, within 2σ, with the energy of our signal.

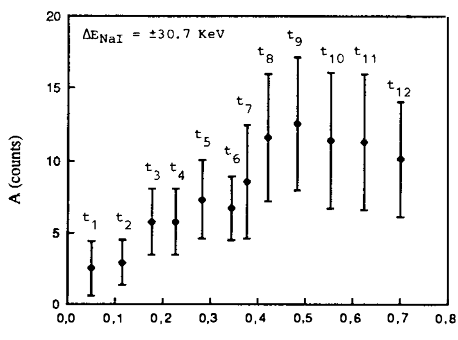

Fig (2): Raw net peak (signal) area evolution with time

A considerable effort has been devoted to the task of seeing whether the coincidence effect 1483.7 ± 0.5 KeV / 558 ± 15 KeV could be explained by a cascade in the natural background. First of all we have analyzed all the Ge spectra (singles, anticoincidence and coincidence). At the 3σ level all the lines have been identified as coming from natural radioactivity (^{232}Th, ^{238}U, ^{235}U families, ^{40}K) or man-made or radiogenic isotopes (^{60}Co, ^{137}Cs, ^{22}Na, ^{133}Ba). At the 2σ level some weak lines can appear in one specific spectrum as due to statistical fluctuations, but can still be rejected by comparing the different spectra. From the complete chart of coincidence events, no other unidentified peaks have been found at the 2σ level, with the exception of the 1483.7 / 559 KeV one. From this analysis we can conclude that no other source of gamma background than the isotopes listed above is observed in our data. After a careful study of the published decay scheme of these isotopes, no 1483.7 ± 0.5 / 558 ± 15 KeV γ-ray cascade has been found.

As far as the time evolution of the signal is concerned, in Fig(2) the (raw) net peak areas obtained (through a standard maximum likelihood method) from several successive coincidence spectra (E_{NaI} = 559.1 ± 30.7 KeV) recorded at increasing times, have been plotted versus time. A steadily increase of the net signal appears, which could indicate a decay process of a half-life of the order of 10^{22} years. It should be noticed that the last points of the time evolution might also indicate a slowing down of the growth of the signal which might correspond to some process decaying with a rather short half-life, say of $\lambda \sim 1.7$ y^{-1}. This second hypothesis is not inconsistent with the results obtained from the analysis[2)] of the sequence of times of count detection of the coincident events, although we have no candidate for such an hypothetical short half-life decay. Obviously a statistical fluctuation could also have explained such a stationary or decreasing effect. Unfortunately, the small number of counts contributing to the coincidence effect, impede us to conclude whether or not the time distribution of events follow a Poisson law. As far as the topology is concerned, the events are uniformly distributed among the Ge detectors, but the small statistics makes rather unreliable any conclusion concerning the spatial distribution in the NaI scintillators. Even if the statistic is quite low, the geometrical distribution shows that almost all the detectors, and not only a few, have contributed to the coincidence data.

3. CONCLUSION AND COMMENTS

We have found a coincidence effect at E_{Ge} = 1483.7 ± 0.5 KeV and E_{NaI} = 558 ± 15 KeV, at the level of 2.5σ, at energies compatible (within 2σ) with the last $Q_{2\beta}$ value of the $^{76}Ge(0^+) \rightarrow$ $^{76}Se(2^+)$ neutrinoless transition, and with the value of the energy of the $^{76}Se(2^+) \rightarrow$ $^{76}Se(0^+)$ deexcitation photon. No explanation for such a peak has been found in our analysis of the background. From the time behaviour of the signal no reliable conclusions can be derived; although is not in contradiction with a long half-life process, such a long half-life behaviour is not necessarily derived from the data. The few number of counts contributing to the signal prevent us to draw definite conclusions concerning the spatial topology of the events. In spite of its low statistical significance all these features might be hypothetically atributed to a neutrinoless double beta effect. Let us see which would be the implications of such an assumption. Taking into account the values $N_{2\beta}$ = (13.8 ± 0.8) x 10^{23}, and ε = 0.23 ± 0.01 one would get a half life of $T_{1/2}(0^+ \rightarrow 2^+)$ = (1.1 ± 0.5) x 10^{22} years.

Two other (0^+-2^+) coincidence experiments have reported results which, according to their authors, do not show any signal at all. The UCSB/LBL experiment[4)], for Nt=7.8 x 10^6 cm^3 h, B = 0.23 ± 0.05 c / KeV x y x 10^{23}, Γ_{Ge} = 3 KeV, $\Gamma_{NaI} \approx$ 90 KeV, gets $T_{1/2} \geq 1.3 \times 10^{23}$ years (1σ). More recent results of this group give[4)], $T_{1/2} \geq 2 \times 10^{23}$ years (1σ). A double beta effect of $T_{1/2} \approx$ 10^{22} years would produce in the N t = 7.8 x 10^6 cm^3 x h UCBS / LBL coincidence spectrum, in a 3 KeV (Ge) x 90 KeV (NaI) window (taking into account their energy resolutions), a signal of 31 counts, whereas the background is 21±5 counts. The coincidence experiment of the Osaka group[6)] has been running for 8621 hours. With a background of B=0.25 to 0.42 c/KeV.y.10^{23} according to the run, Nt=5.6 x 10^{23}, Γ_{Ge} = 2.5 KeV (Γ_{NaI} unpublished) and ε=0.3 they get a lower limit of the half life, $T_{1/2} \geq 5.7 \times 10^{22}$ years (1σ).

Finally, the interpretation of the accumulation as a neutrinoless double beta signal deserves, beside the above considerations, several theoretical comments. The theoretically expected[7] $0^+\to2^+$ half-life in the 2n (N^*) mechanisms is of the order of 3×10^{16} (3×10^{14}) $\langle\eta\rangle^{-2}$ years. If the $\langle\eta\rangle$ upper limits ($\leq 2 \times 10^{-8}$) obtained by the Tubingen group[8] from the $(0^+\to0^+)_{0\nu}$ experimental half life limits of ^{76}Ge and ^{128}Te decays are used, one gets $0^+\to2^+$ half lifes which are several orders of magnitude larger than that obtained tentatively from our peak ($\sim10^{22}$ years). On the other hand, the assumed 10^{22} years half-life of the $0^+\to2^+$ transition derived tentatively from our data would imply a right handed admixture limit of $\langle\eta\rangle \sim 10^{-3}$ or 10^{-4}, according, respectively, to the 2n or N^* mechanism, which are also very large compared with those obtained from the Tellurium and Germanium $(0^+\to0^+)$ data[8].

In conclusion, we have found a coincidence effect where a $2\beta/\gamma$ signal was to be expected, and which, to our knowledge, cannot be atributed to the background. However, its small statistical significance, its unconclusive time and spatial behaviour, its unexpected small half-life ($\sim 10^{22}$ y) compared with the theory, and the fact that other experiments (which probably should not have missed the effect) have not seen any signal, make rather questionable to positively conclude that we are seeing a double beta effect.

The experiment was performed in collaboration with J. Busto, D. Dassie, Ph. Hubert, P. Larrieu, F. Leccia, P. Mennrath and M. M. Villard, from Centre d'Etudes Nucléaires de Bordeaux-Gradignan. The authors would like to thank the IN2P3 (France) and the CAICYT (Spain) for the financial support and all the physicists and technical staff of the Frejus underground laboratory for their valuable assistance. The collaboration of A. Guiral, B. Gerona and R. López is also appreciated.

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