RESULTS OF A SEARCH FOR DOUBLE POSITRON DECAY AND ELECTRON-POSITRON CONVERSION OF ^{78}Kr

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Abstract

The preliminary resulta of a search for the $2\beta^+$ and $K\beta^+$ in a coincidence experiment using a high pressure ionization chamber of enriched ^{78}Kr inside NaI scintillators are presented. After 4434 hours of counting time the half-life limits obtained are $T_{1/2}(K\beta^+)_{0\nu} \geq 5.8\times10^{21}$ y and $T_{1/2}(2\beta^+)_{0\nu+2\nu} \geq 2.0\times10^{21}$ y at 68% C.L. These are the best world limits for the $2\beta^+$ and $K\beta^+$ decay modes.

On general grounds, it is established that the $2\beta^+$ decay rates 1,2,3) are about six orders of magnitude lower than the $2\beta^-$ decay of emitters of the same region of nuclides (say ^{78}Kr versus ^{82}Se), when assuming similar nuclear matrix elements. That strong reduction stems from the smaller energy available and the Coulomb repulsion factor in the positron emission. The cleaning of the background implied by the annihilation photons (when performing coincidence experiments) might somehow compensate the smallness of the expected rate. A favourable nuclear matrix element also enhance the rate bringing it to more optimistic perspectives. Notice that no detailed theoretical estimates are available. On the other hand the electron-positron conversion is a more probable process than the double positron emission because of the higher available energy and the smaller Coulomb repulsion. The relative rates are roughly a factor 10^3-10^4 for the two neutrino mode with respect to the corresponding $2\beta^+$ emissions.

Suitable candidates because of their experimental capabilities as detectors themselves or because of a favourable theoretical expected rate are the $2\beta^+$ emitters ^{78}Kr, ^{124}Xe and ^{106}Cd, the last one being particularly favourable from the theoretical point of view. There are no theoretical estimates of the ^{78}Kr processes expect in the simple [4] or naive [5] approaches. On the other hand, the phase space integrals appearing in the ^{78}Kr and ^{124}Xe cases have been recently computed by using relativistic wave functions for the lepton[6].

The ^{78}Kr transition to ^{78}Se has a Q-value of 2.881 Mev and the transitions (A,Z) - (A,Z-2) are indicated in the scheme depicted in Figure 1. The three processes, double positron emission, electron captured followed by positron emission and double electron capture are energetically allowed for the transitions to the ground states. Transitions to the excited states of ^{78}Se are also possible, but they are no considered here. We are interested in exploring the processes $2\beta^+$ and $K\beta^+$ searching for the coincidences (with and without neutrino emission) between the positron(s) signal recorded in a source-detector high pressure ionization chamber (IC) of krypton gas (enriched in the isotope 78) and the

511 kev annihilation photons detected in a set of sodium iodine detectors which surround the chamber. The signature of the neutrinoless ^{78}Kr - ^{78}Se electron-positron conversion would be an energy deposition of 1859 keV in the IC (positron kinetic energy plus the selenium K-shell binding energy) in coincidence with the two annihilation gammas in the NaIs, whereas the $2\beta^+$ decay would show up as four annihilation gammas in the scintillators coincident with a positron deposition energy of 837 keV in the IC. In the case of no operation of the IC, i.e. when using the chamber only as a source of potential emitters, the recording of gammas will only provide inclusive $(0\nu + 2\nu)$result.

The experimental device consists of a high pressure, high resolution ionization chamber placed within an hexagonal system of large NaI scintillators. The dimensions of the IC are 10.6 cm of diameter and 14.0 cm long, and its internal volume V=1.54 liters. The wall is 2 mm thick, acting as the grounded cathode. The central anode has a diameter of 12 mm. Surrounding the central anode, there is a grid of 40 mm diameter, formed by wires on tungsten (50 μm of diameter) spaced 2 mm. With these parameters, the estimated shield inefficiency of the grid is less than 3.5%. The body flanges and electrodes of the chamber have been made in titanium. Quartz has been used as insulator. The chamber is filled with 35 liters (fiducial volume) of Krypton gas, isotopically enriched up to 94.15% in ^{78}Kr, to be used both as double beta decay source and as detector medium at a pressure of 25 atmospheres. The total number of potentially double beta emitters in the chamber is $N_{2\beta} = 1.024 \times 10^{24}$ atoms of ^{78}Kr. The operating conditions were: grid voltage V_g=+1000V, anode voltage V_a=+2600 V, cathode is grounded; a pressure is 25 atmospheres. The energy resolution achieved with a mixture of $^{78}Kr + 0.2\% H_2$ is fairly good. In the energy regions relevant for the $2\beta^+$ and $K\beta^+$ neutrinoless searches, one can quote, conservatively, an energy resolution of 3% at 837 keV and 2% at 1859 keV as deduced from the nearby ^{88}Y gamma lines of 1836.2 keV, 898.0 keV and 814.2 keV (1836.2 keV - 2x511 keV).

The scintillator system is composed of a set of six large BICRON NaI detectors of dimensions 15.94 cm of diameter and

23.30 cm long, of hexagonal cross-section. The detectors are made from especially chosen low-background materials and have been underground for more than four years before the starting of this experiment. The dimensions of the crystals are 13.5cm diameter, 20.4cm long and are wrapped in teflon, canned in low background steel, 0.5 mm thick, having quartz windows and standard magnetic shielding. The measured energy resolution of the NaI is 6% at the ^{60}Co line of 1.33 MeV. The six hexagonal detectors have been arranged in a honeycomb-like structure, leaving the central hexagonal hole to host the ionization chamber (see Figure 2). A 20 cm layer of low activity lead bricks shields the detectors from enviromental radioactivity.

The experiment has been carried out in the Canfranc Tunnel Laboratory (Spanish Pyrenees) at a depth of 675 m w.e. The acquisition system for the experiment is a fast-slow coincidence device using NIM and CAMAC electronics. The first scintillators open a 100 ns coincidence window in a CAMAC multiplicity arithmetic logic unit which construct the scintillators configuration mask(scintillators fired during the coincidence time) and generate a look at me signal through the Camac bus weaking an interrupt service routine in the PDP 11/73 computer. For each event, we store in a hard disk the configuration mask, the time of the day with a 20 ms precision, the energies of the scintillators fired, as wellas the corresponding time distributions. The slow coincidence is done by opening a 60 μs window and looking the energy detected by the chamber as well as the time difference distribution between the scintilletors (acting as start) and the chamber signal (stop) in a range of about 60 μs. The chamber energy is also stored in the same way as before. In order to minimize the access time to disk we use a software flip-flop between two 2Kw, 16 bits, buffers which fill a big 16 Kw, 16 bits, buffer in memory which is transferred to disk when full.

To compute the efficiency of the photon(s) detection by the NaI array a standard Monte Carlo simulation was used. It was found that after an atom of ^{78}Kr $K\beta^+$ decays in the active volume of the chamber the probability of detecting two 511keV gammas generated in the active volume of the chamber in any pair of scintillators is $\varepsilon_{2\gamma}=0.19$. We note that the coincidences between adjacent sodium iodines are negligible, so the two gamma coincidences refer mostly to opposite scintillators and non-opposite but non-adjacent scintillators. On the other hand, the probability of detecting two 511 keV gamma in any pair of NaI detectors in coincidence also with an energy deposit of 1850 keV in the IC has been computed by MC to be 2.8%. In the case of a $2\beta^+$ decay following the annihillation of both positrons inside the krypton volume, the probability of detecting the two pairs of 511 keV gamma rays in any set of four different detectors is 1.7%.

To give a half life limit of the neutrinoless electron followed by positron conversion we have accumulated 4434.5 hours of three-fold coincidence data. Recording the chamber signals in coincidence with the two 511 keV photons allows to distinguish between the positron annihilation inside the krypton gas from those two 511 keV gamma coincidences due to other background sources. The two annihilation gamma ray coincidence background registrated also in coincidence with a IC signal (of unspecified energy) is 0.026 c/h (for opposite NaIs), 0.022 c/h (for non opposite, non adjacent NaIs) and 0.007 c/h (for adjacent ones), i.e. a reduction by factors 20, 40 and 500 with respect to the corresponding annihilation coincidence backgrounds obtained with a vessel of similar dimensions containing about one third less atoms of ^{78}Kr.

To set a lower limit for the neutrinoless $K\beta^+$ process in ^{78}Kr we have looked for the coincidences between 2γ's in their respective energy windows each one of $2.35\sigma=54$ keV width centred around 511 keV and a IC signal of energy 1859 ± 200keV. Even in such a large IC window there were no events at all in the 4434.5 hours of counting time (versus about two hundred and fifty events recorded when the IC was also fired by the coincidence but without selecting any energy deposited in it). To derive half-life limits we have used the standard expression $T_{1/2} \geq \ln 2 N_{2\beta} \varepsilon tk/A$ where A is the upper limit of the events searched for and k the probability of the events to fall in the searched energy bin(s). The factor ε stands for the efficiency which according to the process under consideration was given above. The half-life limit obtained from the absence of events taking into account $N_{2\beta}=1.024x10^{24}$, $t=0.506y$, $\varepsilon_{K\beta^+}=0.028$ and $k = (0.76)^2$ is

$$T_{1/2}(K\beta^+)_{0\nu} \geq 5.8x10^{21}\ y,\quad 68\%C.L.$$

A very conservative 2ν -mode half-life limit for the process $K\beta^+$ can be quoted if we assign the registered counts in the upper part of the coincidence spectrum shown in Fig.3 ($N(E>700$ keV$)=141$ events) to the corresponding area of the theoretical spectrum[6] of the two-neutrino decay mode in the process $K\beta^+$ of ^{78}Kr. This has been a usual procedure employed to get half-life limits, avoiding the higher background of the low energy region which would mask the double beta signal. By using the fact that the theoretical upper part of the 2ν spectrum accounts for 2/3 of the total number of double beta counts (E=700 keV is the energy of the maximum of the theoretical 2ν spectrum), one gets, using the standard half-life formula cited above. However, this estimation may be significantly improved. Matter of fact, visible peaks in the Fig.3 at the energies about 0.45 MeV, 0.73 MeV, 1.2 MeV and may be even 1.6 MeV are consequences of the e^+-e^- pair production inside the IC by gammas of 1.46(^{40}K)MeV, 1.76(^{214}Bi)MeV, 2.204(^{214}Bi)MeV and 2.62(^{208}Tl)MeV. Therefore, a real quantity of counts inside the IC which could be refered to the $K\beta^+_{2\nu}$ decay of ^{78}Kr will be much less and the respective limit be much higher. The present limit without above mentioned consideration is $T_{1/2}(K\beta^+)_{2\nu} \geq 2x10^{20}y$, 68%C.L.

Finally we have looked also for coincidences of four annihilation gammas in the NaIs together with a signal output from the IC (intended at an energy of 837 keV in a given window). In fact, after 4954.25 hours of counting time no coincidences of four gamma showed up independently of whatever could have happen in the chamber. In fact, due to the chosen trigger (i.e. NaIs first) nothing was obviously registered by the IC which in this case has played the role of a mere source of double positron emitters. The limit one gets is

$$T_{1/2}(2\beta^+)_{0\nu+2\nu} \geq 2.0x10^{21}y,\quad 68\%\ C.L.$$

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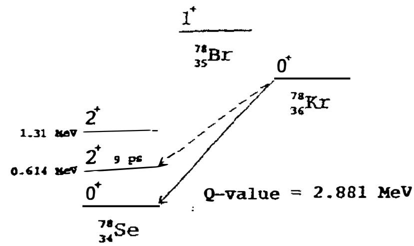

Fig 1: Level scheme of the ^{78}Se -^{78}Br -^{78}Kr triplet.

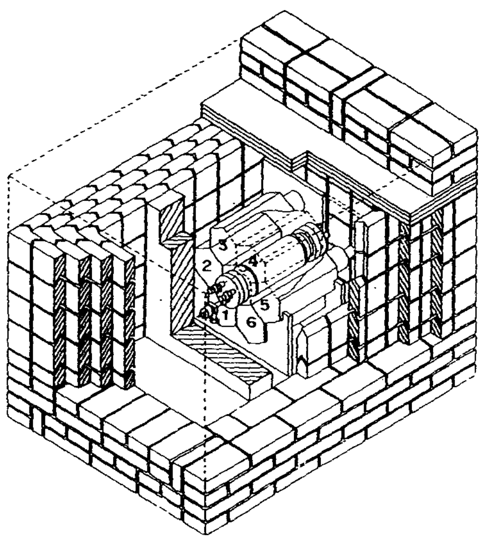

Fig 2: Experimental set-up.

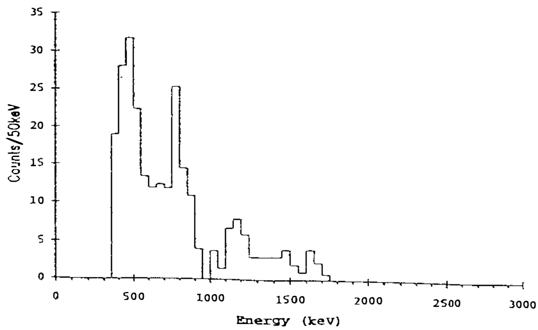

Fig 3: Coincidence spectrum between the IC signal and two 511 keV gammas in the scintillators (within an energy window of 2.35σ) registered in 4434.5 hours.