Search for $0\nu\beta\beta$ decay of ^{48}Ca by CaF$_2$ scintillator

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The observation of the atmospheric and solar neutrino oscillations indicate the existence of non-vanishing neutrino mass. The neutrino oscillation experiments observed transformation of neutrinos from one type to another type which is possible only when there are mass differences and mixing between different types of neutrinos. The absolute scale of neutrino mass and neutrino type (Majorana or Dirac particle) is still unknown. In most grand unified theories, neutrinos are naturally predicted to be massive Majorana particles. The neutrinoless double beta decay (0νDBD) provides the most sensitive test for Majorana neutrino mass.

We have been studying the double beta decay of ^{48}Ca by CaF$_2$ scintillation detector system (ELEGANT VI) located at the underground laboratory (Oto Cosmo Observatory). The Q-value of $^{48}\text{Ca} \rightarrow {}^{48}\text{Ti}$ is highest (4.271 MeV) among potential double beta decay nuclei. The Q-value is far above energies of γ-rays from natural radioactivities (maximum 2.615 MeV from ^{208}Tl decay), therefore we can naturally expect small background in the energy region we are interested in. It also means an advantage of large phase space factor, the highest probability of the occurrence.

The data were taken from middle of 1998, and total live time analyzed was 5567 hours. Total weight of CaF$_2$(Eu) scintillators is 6.66 kg that means a number of ^{48}Ca is 9.61×10^{22} atoms. The total energy spectrum with a statistical significance of 4.23 kg yr after the event selection are shown in Fig. 1 (a). No events were observed in the 0νDBD energy window which is a 3σ peak interval centered at 4.271 MeV.

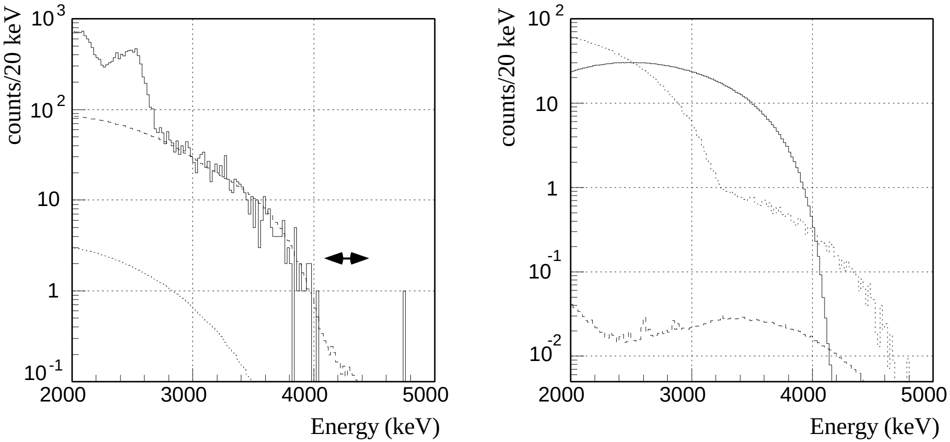
In order to derive the lower limit of the half-life for the 0νDBD, we need to know a number of expected background in this energy window. We considered two possible background source, DBD with two neutrino emission (2νDBD) from ^{48}Ca and the decays (1), (2) and (3) from internal radioactivities of U- and Th-chains. In decays (1) and (2), summed energy of β (endpoint energy of a few MeV) and α (several MeV) particles in electron equivalent energy (quenching factor of CaF$_2$(Eu) scintillators for the α particle was measured to be about 20 %) is recorded in the energy range around 3 – 5 MeV.

$$^{214}\text{Bi} \xrightarrow{Q_\beta = 3.27\text{ MeV}} {}^{214}\text{Po}(T_{1/2} = 164.3\ \mu\text{sec}) \xrightarrow{Q_\alpha = 7.83\text{ MeV}} {}^{210}\text{Pb}, \qquad (1)$$

$$^{212}\text{Bi} \xrightarrow{Q_\beta = 2.25\text{ MeV}} {}^{212}\text{Po}(T_{1/2} = 0.299\ \mu\text{sec}) \xrightarrow{Q_\alpha = 8.95\text{ MeV}} {}^{208}\text{Pb}. \qquad (2)$$

$$^{208}\text{Tl} \xrightarrow{Q_\beta = 5.00\text{ MeV}} {}^{208}\text{Pb}, \qquad (3)$$

The known half-life of the 2νDBD was used to simulate an expected spectrum and plot in Fig. 1 (a). Contribution from the 2νDBD of ^{48}Ca in the 0νDBD energy window is negligible.



(a)

(b)

Figure 1: (a)The comparison of Monte Carlo simulations (dashed line) with experimental data (solid line) of a statistical significance of 4.23 kg yr. Also shown is an expected energy spectrum of 2ν DBD from ^{48}Ca (dotted line). The arrow indicates the 0νDBD energy window. (b)Simulated background events for each decay — dotted line : decay (1), solid line : decay (2) and dashed line : decay (3).

The number of background events from internal radioactive contaminations were estimated by simulations for single and sequential decays. The simulation includes the pulse shape of the scintillators and the gate width of the ADCs (4μ sec). Total simulated energy spectrum from three decays is plotted in Fig. 1 (a) with experimental data. Also shown in Fig. 1(b) are simulated background spectra for each decay mentioned above. The simulation well reproduced shape and vertical scale of the spectrum in 2.8 – 4.0 MeV region. The shoulder at around 2.6 MeV in the experimental spectrum is mainly from ^{208}Tl decay in the CsI(Tl) veto scintillators. Expected number of background events in the 0νDBD energy window is 2.63 ± 0.13 events (^{214}Bi — 2.35 ± 0.12, ^{212}Bi — 0.158 ± 0.006, ^{208}Tl — 0.124 ± 0.007). The detection efficiency was derived to be about 51 % from the Monte Carlo simulation. This value includes the probability of vetoing the true event accidentally.

Following the procedure recommended by PDG [1], we extracted a half-life limit for the 0νDBD of ^{48}Ca. The number of excluded events in the 3σ energy region is 1.18 (0.25) with 90 % C.L. (68 % C.L.). The resulting lower limit of half-life (for the $0^+ \to 0^+$ transition) is

$$\begin{aligned} T^{0\nu}_{1/2} &\geq 8.6 \times 10^{22} \text{ year (68 \% C.L.)} \\ &\geq 1.8 \times 10^{22} \text{ year (90 \% C.L.).} \end{aligned}$$

This result can be converted to the upper limit for the effective Majorana neutrino mass $\langle m_\nu \rangle$. Depending on the theoretical nuclear matrix elements (see Table 8 and 9 in Ref.[2]), the upper bound is

$$\langle m_\nu \rangle < (6.3 - 39.4)\,\text{eV}.$$

References

[1] D.E. Groom et al., (PDG), Europ. Phys. J. **C 15** (2000) 1.
[2] J. Suhonen and O. Civitarese, Phys. Rep. **300** (1998) 123.