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Improved limits on β^- and $\beta^-\beta^-$ decays of ^{48}Ca

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New limits on ^{48}Ca β^- and $\beta^-\beta^-$ decays to excited states of ^{48}Ti have been obtained using a 400 cm^3 low-background HPGe detector and an external source of 24.558 g enriched CaF_2 powder (9.822 g of ^{48}Ca). The limits for β^- decay to the 6^+ ground state, excited 5^+ and 4^+ states in ^{48}Sc are $1.6\cdot10^{20}$ yr, $2.5\cdot10^{20}$ yr, and $1.9\cdot10^{20}$ yr at the 90% confidence level. For the $\beta^-\beta^-$ decay to ^{48}Ti the limits to the first 2^+, second 2^+ and first 0^+ excited states are $1.8\cdot10^{20}$ yr, $1.5\cdot10^{20}$ yr, and $1.5\cdot10^{20}$ yr again at the 90% confidence level.

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The doubly magic nucleus ^{48}Ca can decay by beta decay and double beta decay. The largest possible energy released, 4272 keV, attracts attention to this isotope for double beta decay investigations. However, the small natural abundance (0.187%) and the feasibility problems of producing sufficient quantities of this isotope make studies of rare decays rather difficult. In a previous paper [1] we presented new limits (see Table) on decays of ^{48}Ca. A low-background 400 cm^3 HPGe detector located in the Modane Underground Laboratory (depth of 4800 m w.e.) was used to measure 63.86 g of enriched $^{48}CaCO_3$ powder (enrichment is 73%, 20.18 g of ^{48}Ca were exposed for 797.3 hours). The new upper limits improved by around one order of magnitude were obtained on half-lives of ^{48}Ca for β^- decay to the 6^+ ground state, excited 5^+ and 4^+ states in ^{48}Sc and for the $\beta^-\beta^-$ decay to the first 2^+, second 2^+ and first 0^+ excited states in ^{48}Ti. However the sample was found to have fairly large radioactive impurities, mainly ^{60}Co and ^{226}Ra, which produced a too high background for the processes under investigation and this limited the results. Consequently, we decided to repeat the experiment after the sample was purified.

Several methods of the sample purification were developed using natural calcium with radioactive tracers. Reduction factors of of 10^3 and 10^4 were achieved for $^{226(228)}$Ra and ^{60}Co, respectively. These results were obtained using the same HPGe detector which was used for measurements with enriched Ca samples. Activities of ^{60}Co, ^{226}Ra and ^{228}Th impurities in the enriched Ca sample after purification were found to be less than 2 μBq/g, 4 μBq/g and 2 μBq/g, respectively, that leads to reduction factors of >400, >70 and >25. The chemical purification technique yielded a CaF_2 powder.

The current experiment was performed with the 400 cm^3 HPGe detector and 24.558 g of enriched $^{48}CaF_2$ powder by looking for γ-rays following β^- and $\beta^-\beta^-$ transitions of ^{48}Ca. A total of 9.822 g of ^{48}Ca was exposed for 1589.8 hours.

The HPGe detector is surrounded by a passive shield consisting of 6 cm of archeological lead, 10 cm of OFHC copper and 15 cm of ordinary lead. To reduce the ^{222}Rn gas, which is one of the main sources of the background, special efforts were made to minimize the free space near the detector. In addition, the passive shield was enclosed in an aluminum box flushed with high-purity nitrogen. The cryostat, the endcap and the critical mechanical components of the HPGe detector are made of very pure Al-Si alloy. Finally, the cryostat has a *J*-type geometry to shield the crystal from possible radioactive impurities in the dewar.

The electronics consist of currently available spectrometric amplifiers and an 8192 channel ADC. The energy calibration was adjusted to cover the energy range from 50 keV to 3.5 MeV. The energy resolution was 1.9 keV for the 1332 keV line of ^{60}Co. The electronics were sta-

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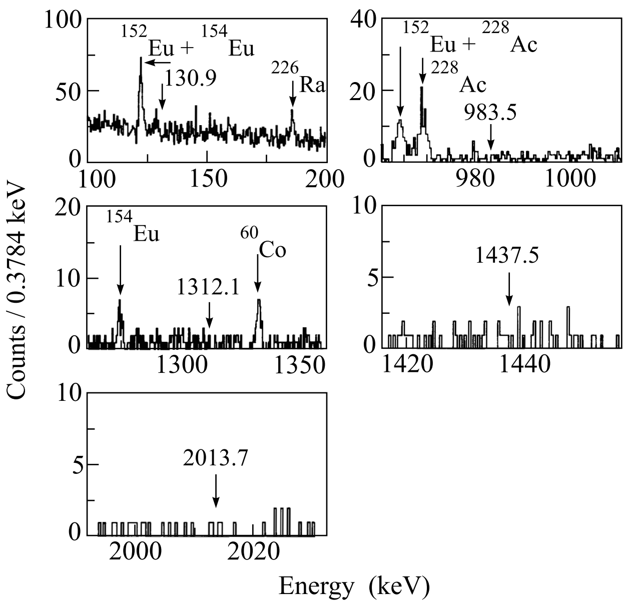
Transition	γ-ray, efficiency	$(T_{1/2})_{\rm exp}, 10^{20}$ yr		$(T_{1/2})_{\rm theor}$, yr
		Present	Previous [1]	
β^- decay				
$0^+ \to 6^+_{\rm g.s.}$	(983.5 keV, 3.25%) + (1312.1 keV, 2.65%)	> 1.6	> 0.71	$1.5 \cdot 10^{29} - 1.3 \cdot 10^{31}$ [3]
$0^+ \to 5^+$	(130.9 keV, 15.2%)	> 2.5	> 1.1	$1.1^{+0.8}_{-0.6} \cdot 10^{21}$ [3]
$0^+ \to 4^+_1$	(130.9 keV, 11.5%)	> 1.9	> 0.82	$8.8 \cdot 10^{23} - 5.2 \cdot 10^{28}$ [3]
$\beta^-\beta^-(0\nu + 2\nu)$ decay				
$0^+ \to 2^+_1$	(983.5 keV, 5.0%)	> 1.8	> 0.47	$5.0 \cdot 10^{26}$ [4]
$0^+ \to 2^+_2$	(983.5 keV, 3.89%) + (1437.5 keV, 2.95%)	> 1.5	> 1.1	$3.6 \cdot 10^{26}$ [4]
$0^+ \to 0^+_1$	(983.5 keV, 4.03%) + (2013.7 keV, 2.33%)	> 1.5	> 0.90	
			> 10* [2]	

Experimental half-life limits and theoretical predictions for the decay of ^{48}Ca. The γ-rays accompanying the different modes are presented with their detection efficiencies. Experimental limits are given at the 90% confidence level. The asterisk * identifies the result for $0\nu\beta\beta$ decay mode taken from [2].

ble during the experiment due to the constant conditions in the laboratory (temperature of 23 °C, hygrometric degree of 50%). A daily check on the apparatus assured that the counting rate was statistically constant.



Partial γ-ray spectra of the energy ranges corresponding to the most intensive γ-quanta of different decay modes of ^{48}Ca which were used to estimate limits. The arrows indicate the expected γ-line positions: 130.9 keV (β^- transitions to 5^+ and 4^+ excited states of ^{48}Sc), 983.5 keV (β^- transition to 6^+ ground state of ^{48}Sc and for all $\beta^-\beta^-$ transitions to excited states), 1312.1 keV (β^- transition to 6^+ ground state of ^{48}Sc), 1437.5 keV ($\beta^-\beta^-$ transition to 2^+_1 excited state of ^{48}Ti), 2013.7 keV ($\beta^-\beta^-$ transition to 0^+_1 excited state of ^{48}Ti)

The detection efficiencies have 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 within 10%.

The background in the regions of interest was found to decrease 5 to 10 times when compared with the previous measurement (figure). One can see from fig.1 there are no statistically significant peaks at pointed places. Using the same method of data analysis [1] the new limits for the decay modes of ^{48}Ca were obtained. Table presents these limits with specified γ-lines and their detection efficiencies using in data analysis. The previous best results and theoretical estimates for the half-lives of the investigated transitions are given for comparison. As one can see the limits have improved by a factor of two or three times when compared with the our previous measurement [1]. Note that the new limits fail to approach the theoretical predictions with the exception of the β^- transition to the 5^+ excited state of ^{48}Sc. For the last transition current experiments can reach the half-life theoretical value.

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