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Search for β and ββ decays in ^{48}Ca

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Abstract

The coincidence technique can offer a useful way to investigate β and ββ decay processes in ^{48}Ca. In this paper the results of a preliminary experimental search are presented. In particular, here the first experimental limit on the half life of the $\beta\beta2\nu(0^+–2^+)$ decay of ^{48}Ca has been obtained; it is $T_{1/2} > 1.2 \times 10^{18}$ y (90% C.L.). © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Large efforts are in progress to search for ββ decay processes by investigating several different isotopes [1]. In particular, recent results by the same authors can be found in Ref. [2].

In the framework of the Standard Model of particle physics (SM) the ββ decay can occur with emission of 2ν. On the contrary, the ββ0ν decay implies a violation of the lepton number conservation of 2 unities and is forbidden in SM where the masses of

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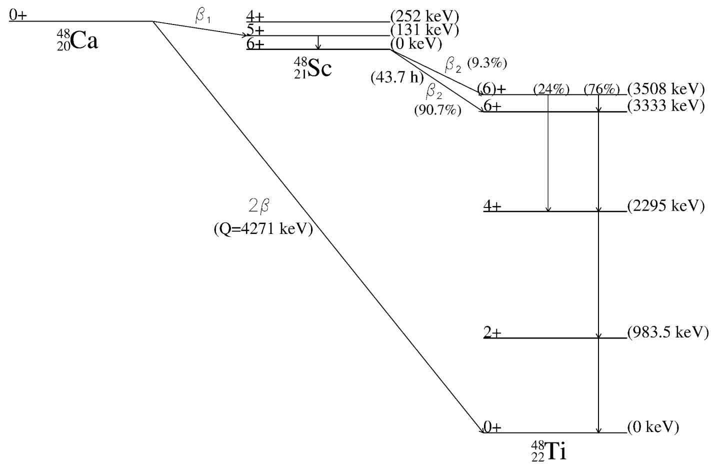

Fig. 1. Single and double β decay of ^{48}Ca.

neutrinos are equal to zero and the leptonic currents can have only left-handed components. Thus, its investigation can give relevant information on the nature of the neutrino, on its mass and on possible right-handed components in the leptonic currents as a sign of new physics beyond SM.

In the present measurement the potentiality of the β–γ coincidence technique has been exploited to search for the ordinary highly forbidden β decay, for the lepton number violating $\beta\beta0\nu(0^+–2^+)$ decay and for the $\beta\beta2\nu(0^+–2^+)$ decay of ^{48}Ca. For this purpose, a 1.11 kg CaF_2(Eu) detector partially surrounded by low background NaI(Tl) detectors has been used deep underground in the Gran Sasso National Laboratory of INFN.

Fig. 1 shows that this technique can be effectively employed to study ^{48}Ca decays; in fact, for example, after a ^{48}Ca β decay, γ of 131 keV is expected by the excited nuclear level of ^{48}Sc and, subsequently, γ of 984, 1037 and 1312 keV are emitted when the daughter ^{48}Sc decays to excited nuclear levels of ^{48}Ti.

At present the best available experimental limit on the ordinary highly forbidden β decay of ^{48}Ca is $T_{1/2} > 6.0 \times 10^{18}$ y (95% C.L.) [3], while the best available experimental limit on the $\beta\beta0\nu(0^+–2^+)$ decay of ^{48}Ca is $T_{1/2} > 1.0 \times 10^{21}$ y (90% C.L.) [4]. No experimental limit on the $\beta\beta2\nu(0^+–2^+)$ decay of ^{48}Ca was instead available before the present work.

2. The experimental setup

The used experimental setup has been installed inside a low radioactive Cu box maintained in high purity (HP) nitrogen atmosphere in slightly overpressure with respect to external environment. It is surrounded by a passive shield made by 10 cm of low radioactive Cu, 15 cm of low radioactive Pb, cadmium foils and about 10 cm of polyethylene/paraffin. The shield is enclosed in a plexiglass box also maintained in HP Nitrogen atmosphere.

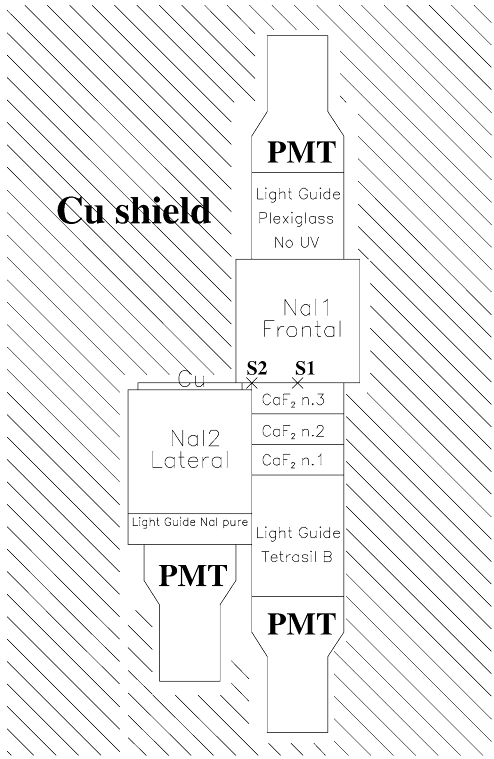

Fig. 2. Schema of the detectors' assembling inside the inner Cu box. The drawing is in scale.

In Fig. 2 the horizontal section of the experimental setup, housed in the inner Cu box, is depicted. As shown there, three CaF_2(Eu) scintillators (3" diameter by 1" length each one) have been glued all together by selected optical grease in order to form a single detector, named 3C. The latter is coupled to a low background EMI9265-B53/FL PMT through a 3" diameter 10 cm long Tetrasil-B light guide. Both the 3C detector and the light guide have been wrapped in teflon tape ($\simeq 0.5$ mm). The considered assembling allows to reduce the number of used PMTs (and related background contribution) and to use two $\simeq$ 4 kg NaI(Tl) as coincidence detectors. In particular, the one named NaI-1 in Fig. 2 is coupled to a low background EMI9265-B53/FL PMT through a 3" diameter 7.2 cm long no-UV plexiglass light guide, while the other one, named NaI-2, is coupled to a low background EMI9265-B53/FL PMT through 1" long pure NaI light guide internal to the detector housing. This assembling is fully surrounded by Cu bricks which fill the Cu box housing the detectors.

To verify that the light absorption in the 3C detector remains at an acceptable level, we have performed devoted calibrations with a collimated ^{241}Am source. For each single CaF_2(Eu) crystal it has been placed at half of its length and the corresponding full energy peak position measured by the 3C detector has been recorded. The results are summarized in Table 1 and show that the attenuation effect in the 3C detector can still be handled

Table 1
Relative light response (R) of each CaF_2(Eu) with respect to the n.1 of Fig. 2

CaF_2(Eu) n.	1	2	3
R	1.0	0.831 ± 0.004	0.845 ± 0.004

by choosing suitable energy windows for the processes searched for. The associated uncertainty has been then estimated by varying the position of the calibration source along the crystal thickness.

Data have been taken by using the following trigger condition: 3C and (NaI-1 or NaI-2), which is suitable not only to study the β decay of ^{48}Ca, but also the possible $\beta\beta(0^+–2^+)$ decays via the investigation of β–γ coincidences. For each detector two ADC channels are acquired: in case of NaI-1 and NaI-2 one is attenuated (ADCHE) by 12 db with the respect to the other (ADCLE), while in case of 3C the attenuation is 20 db. Moreover,

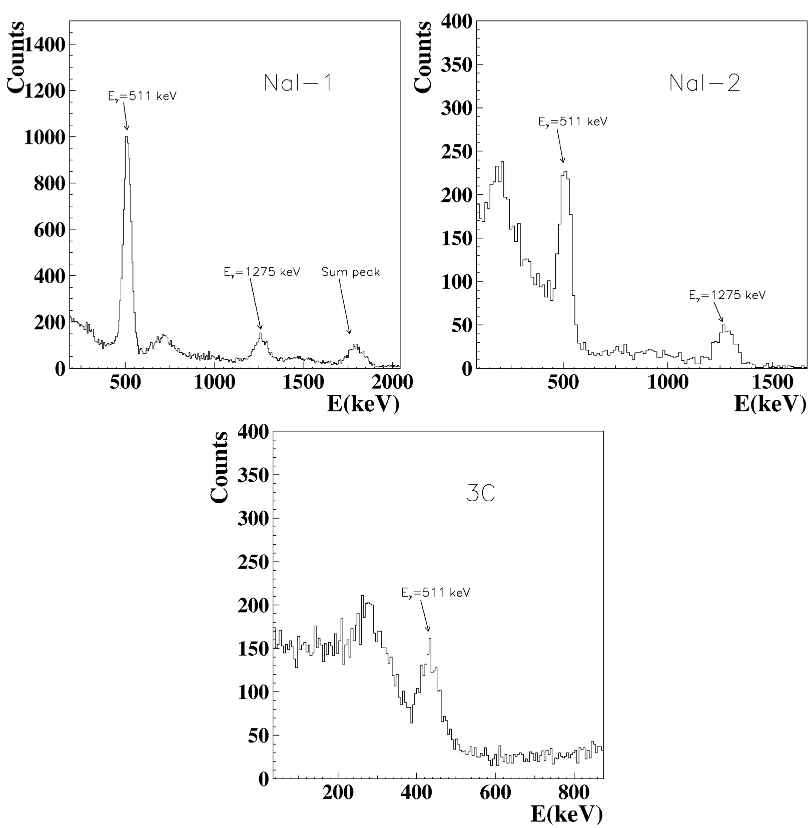

Fig. 3. Energy distributions measured by NaI-1, NaI-2 and 3C detectors when using a ^{22}Na source; see text. The energy scale of the 3C detector is referred to the equivalent energy of the first CaF_2(Eu) detector; therefore, the photopeak position in the 3C energy distribution is at lower energy than the one expected in case of absence of light attenuation.

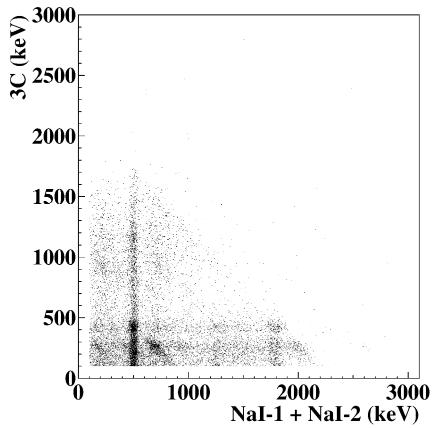

Fig. 4. Bidimensional plot of the γ–γ coincidences between NaI-1 or NaI-2 and 3C measured by using a ^{22}Na source. The energy deposited in the two NaI(Tl) detectors and the energy deposited in the 3C detector are reported. In particular, for the 3C detector the Compton edge and the peaks corresponding to $E_\gamma = 511$ keV and 1275 keV are evident (see also Fig. 3). The same peaks are also evident—with higher energy resolution—for the two NaI(Tl) detectors.

the signals from NaI-1 and NaI-2 are registered by two different channels of a transient digitizer LeCroy 2262 (80 MSample/s sampling frequency of each channel).

The energy distributions collected by the three detectors (3C, NaI-1 and NaI-2) when using a ^{22}Na source are shown in Fig. 3, while Fig. 4 is a bidimensional plot of the γ–γ coincidences measured under the trigger condition given above for the same ^{22}Na source. The ^{22}Na source was placed in between the 3C and the NaI-1 detectors at the center of the contact surface (S1 in Fig. 2), while generally the radioactive sources have been placed in the S2 position of Fig. 2 where the three detectors can be irradiated with maximum efficiency. Here and hereafter when quoted, the energy scale of the 3C detector is referred to the equivalent energy of the first CaF_2(Eu) detector; therefore, since the used γ sources irradiate the whole 3C detector and (due to the low Z of the absorber material) the γ energy is generally released in all the three CaF_2(Eu) detectors, the photopeak position in the 3C energy distribution is at lower energy than the one expected in case of absence of light attenuation (see Fig. 3). Finally, the energy resolution of the 3C detector has been evaluated by matching the Monte Carlo expectations on the measured energy spectra of several calibrations with γ sources; it is: $\sigma/E = 0.045/\sqrt{E(\mathrm{MeV})}$.

3. The search for ^{48}Ca single β decay

An ordinary β decay of $^{48}\mathrm{Ca}(0^+) \to {}^{48}\mathrm{Sc}(6^+, 5^+, 4^+)$ is possible. The calculated half-life of the most probable transition $^{48}\mathrm{Ca}(0^+) \to {}^{48}\mathrm{Sc}(5^+)$ ($Q = 281$ keV [5]) is $T_{1/2} = 7.6 \times 10^{20}$ y [6] and $1.1^{+0.8}_{-0.6} \times 10^{21}$ y [7], while the best available experimental limit is $T_{1/2}(^{48}\mathrm{Ca}, \beta) > 6.0 \times 10^{18}$ y (95% C.L.) [3].

Here such a process has been investigated by searching in the experimental data for the β decay of the daughter nuclei $^{48}\mathrm{Sc} \to {}^{48}\mathrm{Ti}$ with $T_{1/2} = 43.7$ h. With large probability

Table 2
Results on the investigation of the coincidence triggers quoted in the text for the highly forbidden β decay of ^{48}Ca

Case	Energy windows		ϵ	N_d	$T_{1/2}$ (y)
	NaI-1 (keV)	NaI-2 (keV)	$E_{3C} > 100$ keV		(90% C.L.)
(a)	945–1078	–	0.043	-2300 ± 2600	$> 1.8 \times 10^{18}$
(b)	1263–1361	–	0.017	800 ± 4700	$> 4.9 \times 10^{17}$
(c)	–	937–1087	0.043	-1200 ± 2400	$> 1.5 \times 10^{18}$
(d)	–	1251–1373	0.017	3700 ± 6300	$> 2.9 \times 10^{17}$
Combined result					$> 2.4 \times 10^{18}$

The 3C coincidence efficiency for signals with energy above 100 keV is also quoted; its effect is already accounted in the given N_d obtained by the fit procedure. The combined result (by considering the weighted mean of the obtained N_d) is also quoted.

(90.7%) the decay goes to the excited 6^+ level of ^{48}Ti with excitation energy 3333 keV. In this case the emitted electron has energy up to 657 keV, and three γ quanta are emitted as well with energies 1037, 1312 and 984 keV [5]. In the remaining 9.3% of the cases the daughter nucleus ^{48}Sc decays to ^{48}Ti level with energy 3508 keV (electron energy up to 482 keV); the subsequent emitted γ are depicted in Fig. 1. Thus, the coincidence technique can be used to determine the half life of the β decay of ^{48}Ca since the ^{48}Ca–^{48}Sc chain is in equilibrium.

The energy distributions expected for the considered processes have been calculated by Monte Carlo method using the EGS4 code [8] and accounting for the physical parameters of the experimental setup. In this way the related efficiencies in the considered energy windows can be determined (see Table 2).

The coincidence data collected during 3235.72 h have been analyzed by investigating all the possible coincidence triggers. The more stringent results have been obtained for the detection channels which require a signal with energy greater than 100 keV in 3C and, respectively:

(a) one γ in NaI-1 in the (945–1078) keV energy window;
(b) one γ in NaI-1 in the (1263–1361) keV energy window;
(c) one γ in NaI-2 in the (937–1087) keV energy window;
(g) one γ in NaI-2 in the (1251–1373) keV energy window.

The energy windows quoted above for the cases (a) and (c) are obtained by considering the peak position of the 984 keV minus 1σ (lower limit of the window) and the peak position of the 1037 keV plus 1σ (upper limit of the window), since these peaks are not resolved because of the energy resolution of the NaI. In the cases (b) and (d) they represent instead the 1σ approach for the γ of 1312 keV. The different energy resolution of the two NaI(Tl) detectors has been taken into account. As an example, for the trigger condition (a), the expected behaviour of the signal energy distribution in the 3C detector is shown in Fig. 5 together with the energy distribution measured by 3C deep underground. In Fig. 5(a) the energy deposited in the 3C detector is the sum of the β energy and of the energy released by either 0 or 1 or 2 de-excitation γ.

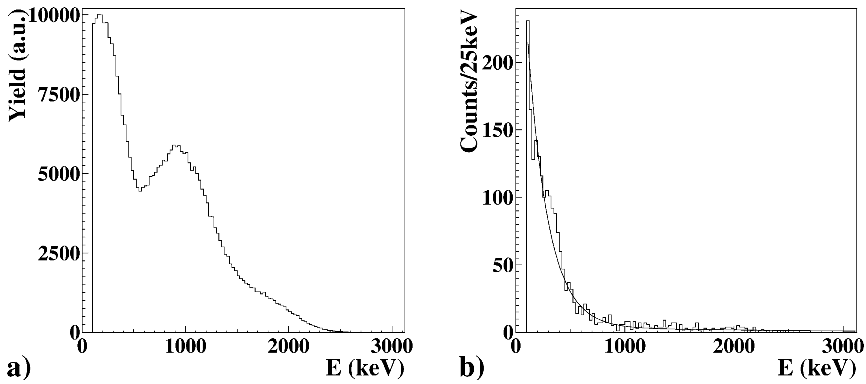

Fig. 5. (a) Behaviour of the energy distribution expected for the signal in the 3C detector due to single β decay of ^{48}Ca in the case: one γ in NaI-1 in the (945–1078) keV energy window and a signal with energy greater than 100 keV in 3C. Here the energy deposited is the sum of the β energy and of the energy released by either 0 or 1 or 2 de-excitation γ. (b) Experimental energy distribution measured by the 3C detector in the same case (superimposed the fit).

Following a widely used procedure, the behaviour of the background in the experimental energy distribution has been fitted in the considered energy interval for each case of interest by an empirical formula. Here we consider the relation[1]

$$F_{P_1\ P_2\ P_3\ P_4}(x) = P_1 + P_2 \cdot x + e^{(P_3 + P_4 \cdot x)}.$$

Thus, the number of events N_d, which could be ascribed to the considered decay process, has been calculated by minimizing (with respect to the P_1, P_2, P_3, P_4 and N_d free parameters) the function:

$$Z^2 = \sum_k \frac{(F_{P_1\ P_2\ P_3\ P_4}(E_k) + N_d \cdot M_k - N_k)^2}{N_k},$$

where the sum is performed in the chosen energy window. There:

(i) E_k is the mean energy of the kth energy bin;
(ii) $N_d \cdot M_k$ are the expected counts in the kth energy bin as evaluated by the Monte Carlo code;
(iii) N_k are the measured counts in the given running period and in the kth energy bin.

The Z^2 function has a χ^2 profile; the minimization program uses the well known MINUIT package [9] and the MINOS routine is used for the right evaluation of all the errors of the free parameters of the fit. To evaluate $T_{1/2}$ the known relation $T_{1/2} = (N \cdot T/N_d)\ln 2$, where N is the number of atoms of ^{48}Ca (here 1.60×10^{22}) and T is the running time (here 3235.72 h), has been used.

The results obtained for the four considered coincidence channels are summarized in Table 2. The cumulative result, obtained by considering the weighted mean of the N_d of

[1] Other reasonable parameterizations give substantially similar results.

each considered coincidence channel, gives $T_{1/2} > 2.4 \times 10^{18}$ y at 90% C.L. for the highly forbidden β decay of ^{48}Ca.

4. ^{48}Ca ββ0ν(0^+–2^+) decay

The ββ0ν(0^+–2^+) decay process has been searched for by investigating β–γ coincidences ($E_\gamma = 984$ keV). The various possibilities for coincidences in the used setup have been exploited. The more stringent result for this ββ0ν(0^+–2^+) decay has been obtained by considering the double coincidence channel given by the photon in the NaI-1 detector (considering an energy window $\pm 2\sigma$ around the 984 keV full energy peak) and the two β with total energy above 2600 keV (efficiency equal to 0.031) in the 3C detector. The behaviour of the energy distribution in the considered energy window expected in the 3C detector for the ββ0ν(0^+–2^+) signal giving these β–γ coincidences has been calculated by the Monte Carlo method using the EGS4 code [8] and accounting for the physical parameters of the experimental setup; it is shown in Fig. 6.

Zero events have been found satisfying the requirements. This gives an upper limit on the number of events, which could be ascribed to the process equal to 2.3 events at 90% C.L. [10] and, consequently, the limit (90% C.L.) $T_{1/2} > 5.5 \times 10^{19}$ y. We note that this limit is lower than the one quoted in Ref. [4].

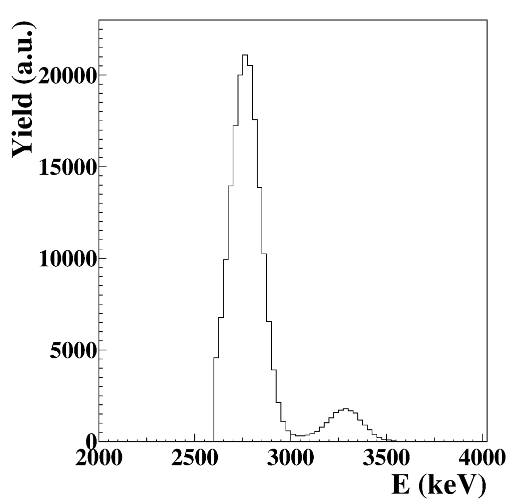

Fig. 6. Behaviour of the energy distribution expected in the 3C detector for the ββ0ν(0^+–2^+) signal considering the β–γ double coincidence given by the de-excitation photon in the NaI-1 detector (energy window $\pm 2\sigma$ around the 984 keV full energy peak) and the two β with total energy above 2600 keV in the 3C detector. The two peaks are due to the different response of the three CaF_2(Eu) detectors (see Table 1); in particular, the highest energy one is due to decay processes occurred in the first CaF_2(Eu) detector and is depressed with the respect to the other one because of the geometry (see Fig. 2).

5. ^{48}Ca $\beta\beta2\nu(0^+–2^+)$ decay

The $\beta\beta2\nu(0^+–2^+)$ has been investigated by searching for β–γ coincidences ($E_\gamma = 984$ keV). Two cases have been considered in the analysis requiring a signal with energy greater than 100 keV in 3C and:

(a) the γ in NaI-1 within the energy window: (945–1023) keV (1σ);
(b) the γ in NaI-2 within the energy window: (937–1031) keV (1σ).

In particular, Fig. 7 shows the expected behaviour of the signal energy distribution in the 3C detector for the case (a) and the experimental energy spectrum under the same (a) requirements.

In both cases the same procedure described in the previous section has been followed. The obtained results are summarized in Table 3. The cumulative result, obtained by

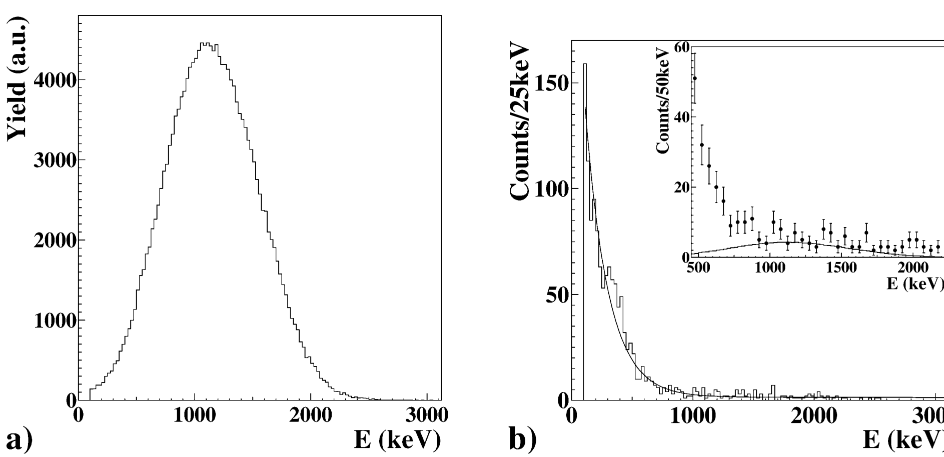

Fig. 7. (a) Behaviour of the energy distribution expected in the 3C detector for the $\beta\beta2\nu(0^+–2^+)$ signal in the case: one γ in NaI-1 in the (945–1023) keV energy window and a signal with energy greater than 100 keV in 3C; (b) experimental energy distribution measured by the 3C detector for the same case (superimposed the fit). In the inset the experimental data points are compared with the expectation for the considered decay process when $T_{1/2}$ would be equal to the found 90% C.L. limit (see Table 3).

Table 3
Results on the investigation of the coincidence triggers quoted in the text for the $\beta\beta2\nu$ $(0^+–2^+)$ decay of ^{48}Ca

Case	Energy windows		ϵ	N_d	$T_{1/2}$ (y)
	NaI-1 (keV)	NaI-2 (keV)	$E_{3C} > 100$ keV		(90% C.L.)
(a)	945–1023	–	0.026	-300 ± 2200	$> 1.2 \times 10^{18}$
(b)	–	937–1031	0.024	2000 ± 3800	$> 5.0 \times 10^{17}$
		Combined result			$> 1.2 \times 10^{18}$

The 3C coincidence efficiency for signals with energy above 100 keV is also quoted; its effect is already accounted in the given N_d obtained by the fit procedure. The combined result (by considering the weighted mean of the obtained N_d) is quoted.

considering the weighted mean of the N_d of each considered coincidence channel, gives $T_{1/2} > 1.2 \times 10^{18}$ y at 90% C.L. for the $\beta\beta 2\nu$ (0^+–2^+) decay of ^{48}Ca.

For the sake of completeness, we note that the background events in the (900–1700) keV energy region (where most of the signal is expected) of Fig. 7(b) can be mainly ascribed to double coincidences from the standard contaminant ^{208}Tl (e.g.—in the $\simeq$ 44% of the cases—583 and 2614 keV γ); this is credited by the whole coincidence bidimensional spectrum. Other contributions can arise from the tails of coincidences induced, e.g., by ^{214}Bi (mainly 609—1120 keV γ) and ^{40}K (through Compton scatterings).

6. Conclusion

The coincidence technique has been applied to search for the highly forbidden β decay of ^{48}Ca and for its $\beta\beta(0^+$–$2^+)$ decays by using a 1.11 kg CaF_2(Eu) scintillator partially surrounded by low background NaI(Tl) detectors. The achieved limits on $T_{1/2}$ (90% C.L.) are:

(i) 2.4×10^{18} y for the ^{48}Ca β decay;
(ii) 5.5×10^{19} y for the ^{48}Ca $\beta\beta 0\nu(0^+$–$2^+)$;
(iii) 1.2×10^{18} y for the ^{48}Ca $\beta\beta 2\nu(0^+$–$2^+)$.

The $T_{1/2}$ limit for the ^{48}Ca β decay is roughly of the same order of magnitude than the best available limit, supporting that competitive results can be achieved by covering the whole solid angle with coincidence detector(s), by achieving a larger exposure and by obtaining further reduction of the U/Th residual contaminations. As regards the $\beta\beta 0\nu(0^+$–$2^+)$ process, the obtained limit is about 18 times lower than the best available one, while the limit on the $\beta\beta 2\nu(0^+$–$2^+)$ process has been given here for the first time. Also for these cases, the considerations given above allow to expect significant improvements in near future by exploiting the coincidence technique. In particular, as regards the discovery potentiality of this technique it is in principle not lower than the one of other approaches, requiring analogously the achievements of very large exposure and of very highly radio-pure detectors.

References

[1] V.I. Tretyak, Yu.G. Zdesenko, At. Data Nucl. Data Tables 61 (1995) 43;
E. Fiorini, talk given at TAUP 2001, LNGS, September 2001.
[2] R. Bernabei et al., Nuovo Cimento A 110 (1997) 189;
P. Belli et al., Astropart. Phys. 10 (1999) 115;
P. Belli et al., Nucl. Phys. B 563 (1999) 97;
R. Bernabei et al., ROM2F/2001-26, submitted.
[3] D.E. Alburger, J.B. Cumming, Phys. Rev. C 32 (1985) 1358.
[4] R.K. Bardin et al., Nucl. Phys. A 158 (1970) 337;
A.S. Barabash, Phys. Lett. B 216 (1989) 257.
[5] C.M. Lederer, V.S. Shirley (Eds.), Table of Isotopes, VII ed., Wiley, New York, 1978.
[6] E.K. Warburton, Phys. Rev. C 31 (1985) 1896.

[7] M. Aunola et al., Europhys. Lett. 46 (1999) 577.
[8] W.R. Nelson et al., SLAC-265, UC-32 (E/I/A).
[9] CN/ASD Group, MINUIT User Guide, Program Library D 506, CERN, 1993.
[10] K. Hikasa et al., Particle Data Group, Phys. Rev. D 45 (1992).