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New limits on $2\beta^+$ decay processes in ^{106}Cd

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Abstract

An experiment to study the double positron decay of ^{106}Cd ($\beta^+\beta^+$, β^+/EC or EC/EC) has been performed at the Gran Sasso National Laboratory of INFN. A low background setup with two large NaI(Tl) crystals and cadmium samples (total mass $\simeq$ 154 g), enriched in ^{106}Cd at 68%, have been used. New limits on the half-lives for the different $\beta^+\beta^+$, β^+/EC and EC/EC decay channels in ^{106}Cd have been obtained. They are in the range (0.3–4) $\cdot 10^{20}$ y at 90% C.L., which is significantly higher (by a factor 6 to 60) than those already published for this nuclide. © 1999 Elsevier Science B.V.

1. Introduction

The results already achieved in the investigations of the neutrinoless double beta ($0\nu2\beta^-$) decay have pointed out the great potential of this process – which violates the lepton number conservation – to effectively search for neutrino mass (right-handed admixture in the weak interactions, neutrino coupling constant with Majorons (M), etc.) as sign of a possible new physics beyond the standard model [1,2]. Furthermore, it has been also recently remarked [2–4] that – with the exception of the conventional light neutrino exchange mechanism – the $0\nu2\beta^-$ decay can occur via mechanisms based on: (i) the heavy right-handed neutrino exchange in left–right symmetric models; (ii) the exchange of e.g. gluons, squarks, etc., in R-parity violating SUSY models; (iii) the exchange of sneutrinos in R-parity conserving SUSY models; (iv) the exchange of leptoquarks in leptoquarks models (see [2–4] and references therein). Therefore, at present, the $0\nu2\beta^-$ decay is considered as a powerful test for different extensions of the standard model (including several SUSY models), which could offer not only complementary but – in some cases – competitive and even superior results than other running or forthcoming accelerator and non-accelerator experiments [2–4].

Neutrinoless double positron ($0\nu2\beta^+$) decay, β^+/EC decay and EC/EC decay can give, in principle, the same information as $0\nu2\beta^-$ decay. In addition, whenever the last process would be observed, they would play a key role in recognising the main production mechanism, strongly depending their calculated half-lives on whether the decay is dominated by Majorana neutrino mass or by right-handed admixtures in weak interactions [5]. On the other hand, even the non-observation of the $0\nu2\beta^+$ decay would provide very useful additional and complementary information.

Due to the poor natural abundance of the $2\beta^+$ can-

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didate nuclides and to their lower Q values, the current level of experimental sensitivity offers half-life limits in the range 10^{18}–10^{20} years [1]. They are modest compared with those already achieved in the $2\beta^-$ decay searches, although the present theoretical expectations for the half-lives of some $2\beta^+$ candidate isotopes are favourable [5]. To reach a suitable sensitivity the use of enriched samples is needed to effectively exploit the potentiality of the $2\beta^+$ processes, which have the advantage of a very clear signature. In fact, e.g., in the $0\nu\beta^+$/EC decay the monoenergetic positron will give two 511 keV annihilation γ-rays in addition to characteristic X-rays.

As a first step to fill up the existing gap in sensitivity between $2\beta^-$ and $2\beta^+$ decay data, we present here the results of a study on the $2\beta^+$ decay processes in ^{106}Cd, which is a one of the best candidate nuclides because of its rather high Q value ($\beta^+\beta^+$), (2771 ± 8) keV [7] and to the favourable theoretical estimates for half-lives [5,6].

2. Source, low background setup and measurements

The β^+/EC and $2\beta^+$ decay processes would manifest themselves by the simultaneous emission of two or four 511 keV γ-rays. Therefore, two (or more) low background NaI(Tl) scintillators placed around a ^{106}Cd source can be considered for a well suitable setup to measure these γ-rays in coincidence.

In the present experiment, to overcome the poor natural abundance of the ^{106}Cd (1.25%), the source has been realized by several samples of metallic cadmium enriched in ^{106}Cd at $\simeq$ 68% (total mass $\simeq$ 154 g). One part of these samples ($\simeq$ 109 g) has been purified twice by the method of vacuum distillation, while the other part ($\simeq$ 45 g) was purified only once and, therefore, its radiopurity is expected to be worse. The source was prepared roughly in form of a plate (approximately 37 mm · 70 mm) by putting the enriched cadmium samples inside a thin teflon envelop as tight as possible, but without melting or pressing them. It was, then, placed between two ($4'' \times 4'' \times 4''$) low background NaI(Tl) crystals, mounted with 15 mm space between them. Each crystal was coupled to a low background EMI9265B53/FL photomultiplier, in one case through a 1″ long pure NaI light guide (detector n.1) and in the other one through a 10 cm long TETRASIL-B light guide (detector n.2). The crystals were wrapped by a 100 μm thick teflon diffuser and their housings were made by 1 mm thick high purity (HP) copper.

To avoid any contact with environmental air (which can contain radon in trace), the source and the detectors were enclosed in a sealed HP copper box inside a low radioactive shield made by 10 cm of copper and 10 cm of lead; the lead was surrounded by a 1 mm Cd foil and about 10 cm of polyethylene. The copper box was flushed with HP nitrogen gas and maintained at about 1 mbar overpressure. Furthermore, the whole shield was enclosed in a plexiglass sealed box also flushed with HP Nitrogen gas. The setup was installed in the Gran Sasso Underground Laboratory providing a shield from the cosmic rays of $\simeq$ 3500 m.w.e.

In the event by event data acquisition two independent spectrometric channels were used; therefore, energy spectra for each detector separately or two-dimension coincidence spectra can be reconstructed from the stored data. In the background measurements the events were recorded only in case of coincidence between the two scintillators and the considered energy window was 200–4100 keV for both channels.

The energy scale and the resolution of each detector was calibrated with a ^{137}Cs source (E_γ = 662 keV) and ^{22}Na (E_γ = 511, 1275 and, their sum, 1786 keV). The last source was also used to perform coincidence calibration between two crystals, exploiting the correlations between the emitted γ-rays (see Fig. 1). In addition, some background peaks from ^{232}Th and ^{226}Ra contamination in the enriched cadmium samples were used for calibration and for monitoring during the whole data taking. These are cascade γ-rays from ^{208}Tl (E_γ = 277, 511, 583, 860, 2614 keV), from ^{228}Ac (E_γ = 270, 327, 409, 463 keV) and from ^{214}Bi (E_γ = 609, 1120, 1238 keV). The energy dependence of the resolution (FWHM) was parametrized according to $\mathrm{FWHM}(E_\gamma) = (a + b \cdot E_\gamma)^{1/2}$, where FWHM and E_γ are given in keV. The fit to the data quoted the following values of the parameters for the first (second) crystal: a = 1570 (1100) keV^2; b = 7.4 (5.9) keV. The energy scale and resolution of both detectors were stable within the statistical uncertainties for the whole running period.

Measurements with the enriched ^{106}Cd samples were performed during 4321 h. The two-dimension

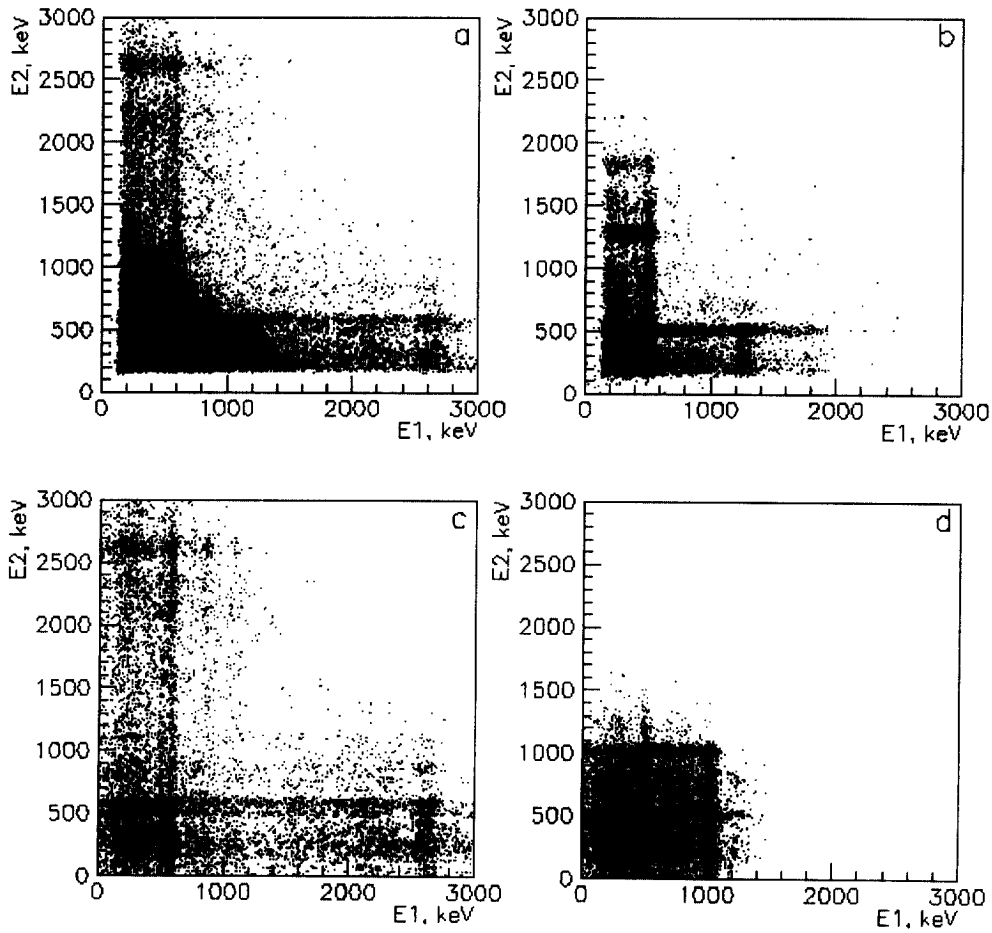

Fig. 1. Two-dimensional coincidence spectra of NaI(Tl) detectors: (a) experimental spectrum measured with enriched ^{106}Cd samples for 1489 h^{-1}; (b) ^{22}Na calibration spectrum; (c) model spectrum of the ^{232}Th decay chain in ^{106}Cd samples; (d) model spectrum of the $2\beta^+$ decay of ^{106}Cd.

coincidence spectrum for the last 1489 h is shown in Fig. 1a[2], where the peaks from ^{214}Bi (E_1 = 609 keV, E_2 = 1120 keV and "vice versa") and from ^{208}Tl (E_1 = 583 keV, E_2 = 2614 keV and "vice versa") can be recognized. These are very clear in Fig. 2, which represents the experimental energy spectrum of the detector n.2 when a coincidence event – with energy deposit exceeding 400 keV – occurs in detector n.1. As mentioned earlier, the presence of these peaks allows us to check the energy scale and resolution of both detectors during the whole experiment; moreover, it allows us to determine the contents of the Th and U contamination in the enriched cadmium samples with the aim of building up a model for the background.

3. Radioactive contamination of the cadmium samples and of the PMTs

Considering the achieved radiopurity in the developments of highly radiopure NaI(Tl) crystals [8], to estimate the locations and quantities of the main radioactive residual pollution in the setup, we put our attention on the contamination of the cadmium samples and PMTs. The coincidence spectra from the ^{232}Th, ^{226}Ra and ^{40}K decays in the enriched cadmium samples and in both PMTs were simulated by using

[2] We consider there a smaller running time to not overload the figure.

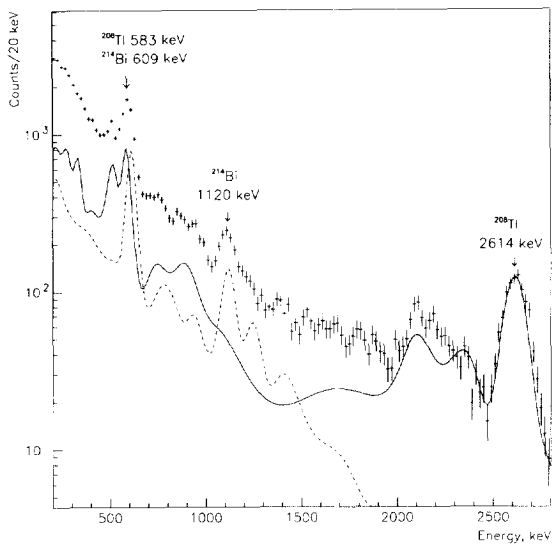

Fig. 2. The background spectrum of the second NaI(Tl) crystal obtained in coincidence with the first detector under the condition that the energy deposit in the last one should exceed 400 keV. It refers to a period of 2851 h, when a larger energy window has been considered. The full and dashed curves are model spectra from ^{232}Th and ^{226}Ra contamination in the ^{106}Cd samples, respectively.

the GEANT3.21 package [9]. To describe the initial kinematics of the events, the event generator DECAY4 [10] was used. It takes into account up to 48 excited levels of daughter nuclei and up to 166 different transitions in the de-excitation processes. Possibilities of emission of the conversion electrons and $\beta^+\beta^-$ pairs instead of γ-quanta, as well as the angular correlation of the emitted particles (the cascade γ-rays, in particular), are also taken into account. As an example, a two-dimensions simulated spectrum from ^{232}Th contamination in the ^{106}Cd samples is shown in Fig. 1c, while the energy spectrum for crystal n.2, according to the model, is depicted in Fig. 2. By comparing model spectra from the ^{232}Th pollution in cadmium samples and PMTs with the experimental data, it was found that only ^{232}Th contamination in the cadmium samples can contribute to the peak at 2614 keV. That allowed a precise determination of the activity of ^{232}Th in the enriched cadmium, namely (0.13 ± 0.01) mBq/g. On the other hand, the presence of two-dimensions peaks at the energies $E_1 = 609$ keV and $E_2 = 1120$ keV, and "vice versa", allows us to calculate the activity of ^{226}Ra in the cadmium samples, which is (0.12 ± 0.04) mBq/g. In accordance with simulations, these two-dimensions peaks from the ^{226}Ra contamination in the PMTs are negligible. Furthermore, the fact that the intensities of these two peaks are different (approximately by a factor 2) implies that the ^{226}Ra pollution is closer to the detector n.1 and proves the assumption that the radiopurity level of the two parts of the enriched cadmium are different.

The simulated spectrum from ^{226}Ra contamination in the ^{106}Cd samples is also shown in Fig. 2; the contribution of ^{232}Th and ^{226}Ra contamination in the enriched cadmium samples to the measured background spectra is about 71% with energy threshold 400 keV for both detectors. The remaining part can be justified by ^{40}K, ^{226}Ra and ^{232}Th pollution in the PMTs and ^{40}K in samples. The fit gives the following values and limits on their activities: (i) < 2 mBq/g for ^{40}K in the ^{106}Cd samples; (ii) (1.8 ± 0.6) mBq/g for ^{232}Th, < 1.3 mBq/g for ^{226}Ra and < 6 mBq/g for ^{40}K in the PMTs.

4. Half-life limits of the $2\beta^+$, β^+/EC and EC/EC channels for the ^{106}Cd

The half-life limits were estimated for the various channels of the ^{106}Cd decay following procedures similar to the one described below in detail for the β^+/EC case. The response functions and detector efficiencies for the different modes of the $2\beta^+$, β^+/EC and EC/EC processes in ^{106}Cd were simulated by using the GEANT3.21 and DECAY4 codes [9,10]; as an example, the two-dimensions coincidence spectrum for $2\beta^+$ decay of ^{106}Cd, calculated according to the model, is depicted in Fig. 1d.

The background spectrum of the detector n.2 in the energy region 400–700 keV, collected during 4321 hours, is shown in Fig. 3. It was obtained under the condition that coincidence events in the detector n.1 are in the window (511 ± 30) keV. The energy spectra from ^{232}Th and ^{226}Ra contamination of the enriched cadmium samples – calculated according to the model and normalized to the determined activities and running time – are also shown in Fig. 3. The energy spectra from the model for ^{40}K, ^{226}Ra and ^{232}Th pollution in the PMTs have a very smooth and decreasing energy dependence, giving a negligible contribution to the energy region 400–700 keV.

The residual energy spectrum between the experi-

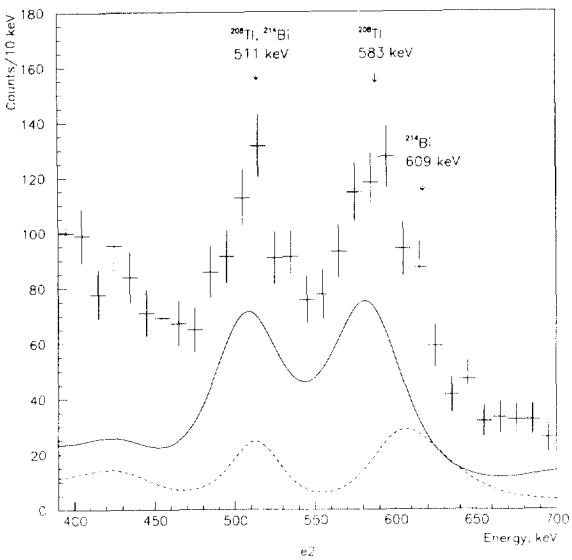

Fig. 3. The background spectrum of the second NaI(Tl) crystal (for 4321 h) obtained in coincidence with the first detector under the condition that the energy lost in the last one was within the window (511 ± 30) keV. The full and dashed curves are model spectra from ^{232}Th and ^{226}Ra contamination in the ^{106}Cd samples, respectively.

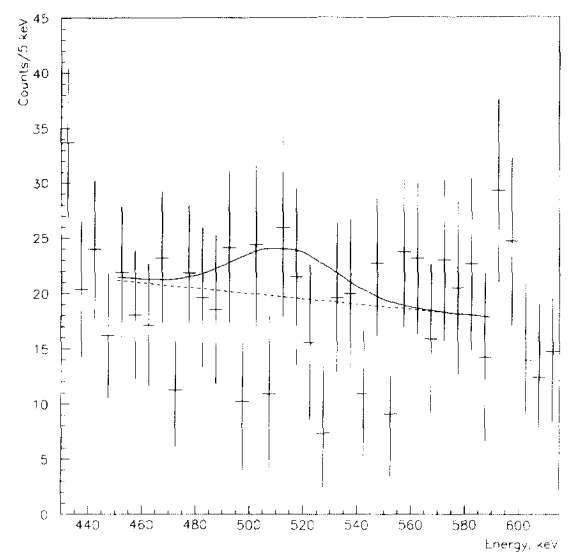

Fig. 4. The residual spectrum between the experimental one of the second NaI(Tl) crystal (from Fig. 3) and model spectra from ^{232}Th and ^{226}Ra contamination of the ^{106}Cd samples. The full curve is the excluded β^+/EC decay peak of the ^{106}Cd corresponding to the half-life of $T_{1/2} \geq 3.7 \cdot 10^{20}$ y (90% C.L.).

mental distribution of Fig. 3 and the ones evaluated by the model from ^{232}Th and ^{226}Ra contamination of the ^{106}Cd samples is depicted in Fig. 4. By using the least-square technique this residual energy spectrum was fitted, in the energy window 450–590 keV, by the sum of two functions: the straight line corresponding to the background and the simulated spectrum of the ^{106}Cd β^+/EC decay. From the fit, the number of events in the β^+/EC decay peak was determined as -30 ± 34, giving no statistical evidence for the effect ($\chi^2 = 0.79$). Using these values, the excluded number of 33 events at 90% C.L. was calculated for the β^+/EC decay of ^{106}Cd, in accordance with the Particle Data Group procedure for the renormalization of the probability function in the physically acceptable area [11]. The detector efficiency in the 511 keV peak for the NaI(Tl) crystal n.2 is equal to 8.4%, taking into account the decrease of efficiency due to the chosen energy window (511 ± 30) keV for the first crystal. It leads (using also the number of ^{106}Cd nuclei and the running time) to the following half-life limit for the β^+/EC decay of ^{106}Cd: $T_{1/2} \geq 3.7 \cdot 10^{20}$ y (90% C.L.). The excluded β^+/EC decay peak corresponding to this half-life limit is also presented in Fig. 4.

The half-life limits for the other modes of the $2\beta^+$, β^+/EC, and EC/EC decay of the ^{106}Cd to the ground and excited states of the ^{106}Pd have been obtained following procedures described above for β^+/EC decay. They are quoted in Table 1 together with the best results from other works [12,13]. The efficiency values, which have been calculated as described above, are also given there with the corresponding energies of the two-dimensions peaks for the different modes and decay channels. We note, in particular, that in the case of neutrinoless EC/EC mode (K- and L-electrons capture) the energy release $Q = (2743 \pm 8)$ keV is practically equal – within the errors – to the energy of ^{106}Pd excited level $1,2^+$ (2741.0 keV) [14]. If this level and the ground state of ^{106}Cd would be degenerated, some resonant effects could enhance the probability of this transition.

Since the efficiency values for the $2\beta^+$, β^+/EC processes with emission of two neutrinos are practically the same as the neutrinoless modes (the difference is visible only for β^+/EC decay to the ground state of the ^{106}Pd), their half-life limits are the same too. This is also true for the neutrinoless processes with emission of Majoron.

Table 1
Experimental half-life limits for the $2\beta^+$ decay processes of ^{106}Cd

Decay mode (transition)	Peak efficiency ($E_1 - E_2$), keV	$T_{1/2}$ limit (90% C.L.) y (this work)	$T_{1/2}$ limit (90% C.L.) y (other works)
β^+/EC (2ν) g.s. → g.s.	9.3% (511–511)	$4.1 \cdot 10^{20}$	$6.6 \cdot 10^{18}$ ($0\nu + 2\nu$) [12]
β^+/EC (0ν+0νM) g.s. → g.s.	8.4% (511–511)	$3.7 \cdot 10^{20}$	$5.5 \cdot 10^{19}$ (0ν) [13]
β^+/EC ($0\nu + 2\nu + 0\nu$M) g.s. → 0_1^+ (1134 keV)	2.8% (511–511)	$1.1 \cdot 10^{20}$	$8.1 \cdot 10^{18}$ ($0\nu + 2\nu$) [12]
β^+/EC ($0\nu + 2\nu + 0\nu$M) g.s. → 2_1^+ (512 keV)	5.7% (511–511)	$2.6 \cdot 10^{20}$	$7.3 \cdot 10^{18}$ ($0\nu + 2\nu$) [12]
β^+/EC ($0\nu + 2\nu + 0\nu$M) g.s. → 2_2^+ (1128 keV)	3.2% (511–511)	$1.4 \cdot 10^{20}$	$7.8 \cdot 10^{18}$ ($0\nu + 2\nu$) [13]
$2\beta^+$ ($0\nu + 2\nu + 0\nu$M) g.s. → g.s.	5.5% (511–511)	$2.4 \cdot 10^{20}$	$2.2 \cdot 10^{19}$ (0ν) [13] $1.0 \cdot 10^{19}$ ($0\nu + 2\nu$) [12]
$2\beta^+$ ($0\nu + 2\nu + 0\nu$M) g.s. → 2_1^+ (512 keV)	3.6% (511–511)	$1.6 \cdot 10^{20}$	$1.0 \cdot 10^{19}$ ($0\nu + 2\nu$) [12]
EC/EC (0ν) g.s.→ $1,2^+$ (2741 keV)	0.71% (512–2229)	$3.0 \cdot 10^{19}$	–
EC/EC ($2\nu + 0\nu$M) g.s. → 0_1^+ (1134 keV)	1.6% (512–622)	$7.3 \cdot 10^{19}$	$6.2 \cdot 10^{18}$ ($0\nu + 2\nu$) [12]
EC/EC ($2\nu + 0\nu$M) g.s. → 2_2^+ (1128 keV)	1.03% (512–616)	$4.9 \cdot 10^{19}$	$5.1 \cdot 10^{18}$ ($0\nu + 2\nu$) [12]

5. Conclusions

In this paper new improved limits on the half-lives of the $\beta^+\beta^+$, β^+/EC and EC/EC processes in ^{106}Cd have been presented; they are in the range $(0.3–4) \cdot 10^{20}$ y (90% C.L.). These limits are significantly higher (by factor 6 to 60) than those already published for the same nuclide, approaching the theoretical estimates of Ref. [5,6,12]. In particular, we note that the $T_{1/2}$ values calculated in [5,6,12] for the β^+/EC(2ν) decay of ^{106}Cd are within $(8–40) \cdot 10^{20}$ y, which are not so far from our limit for this process.

The present results strongly support the interest in filling up the existing gap between $2\beta^-$ and $2\beta^+$ decay experimental data. Therefore, a further enhancement of the experimental sensitivity is under consideration; it includes additional purification of the enriched cadmium samples and the growth from them of a $^{106}CdWO_4$ scintillator, which could be used as source-detector and, in combination with low background NaI(Tl) crystals, could allow to identify signals from the $0\nu 2\beta^+$ decay processes of ^{106}Cd.

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