Physics Letters B 767 (2017) 321–329

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Enriched TeO_2 bolometers with active particle discrimination: Towards the CUPID experiment

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ARTICLE INFO

Article history:
Received 10 October 2016
Received in revised form 12 December 2016
Accepted 6 February 2017
Available online 14 February 2017
Editor: W. Haxton

Keywords:
Double beta decay
Bolometers
Isotope enrichment
Cherenkov emission
Neganov–Luke effect

ABSTRACT

We present the performances of two 92% enriched $^{130}TeO_2$ crystals operated as thermal bolometers in view of a next generation experiment to search for neutrinoless double beta decay of ^{130}Te. The crystals, 435 g each, show an energy resolution, evaluated at the 2615 keV γ-line of ^{208}Tl, of 6.5 and 4.3 keV FWHM. The only observable internal radioactive contamination arises from ^{238}U (15 and 8 μBq/kg, respectively). The internal activity of the most problematic nuclei for neutrinoless double beta decay, ^{226}Ra and ^{228}Th, are both evaluated as <3.1 μBq/kg for one crystal and <2.3 μBq/kg for the second. Thanks to the readout of the weak Cherenkov light emitted by β/γ particles by means of Neganov–Luke bolometric light detectors we were able to perform an event-by-event identification of β/γ events with a 95% acceptance level, while establishing a rejection factor of 98.21% and 99.99% for α particles.

1. Introduction

The following three important questions in neutrino physics will be addressed by next generation neutrinoless double beta decay (0ν-DBD) experiments: are neutrinos Majorana particles that differ from antineutrinos only by helicity? Is lepton number conservation violated? What is the neutrino mass-scale? Searches for 0ν-DBD have been carried out for many decades investigating a large variety of nuclei with many different experimental techniques [1]. However the discovery of the atmospheric neutrinos oscillations by Super-Kamiokande as well as those observed in solar neutrinos by the SNO experiment – both awarded the Nobel Prize in 2015 – boosted these searches, and now is an optimum time to launch next generation 0ν-DBD experiments. Recent analyses of all of the atmospheric, solar, and reactor neutrino oscillations [2] indicate that there exist scenarios in which the effective Majorana mass of the electron neutrino could be larger than 0.05 eV. Within the last few years, the most stringent limits on 0ν-DBD came from EXO-200 [3], GERDA [4] and CUORE-0 [5] while, very recently, the KamLAND-Zen experiment [6] set the strongest limit on this decay, using ^{136}Xe. While recent experimental achievements are impressive, it is difficult to compare results from different isotopes because of the large uncertainties in the nuclear matrix elements.

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http://dx.doi.org/10.1016/j.physletb.2017.02.011

Ultimately, the goal of next the generation 0ν-DBD experiments is to sensitively probe the entire inverted hierarchy region. To reach this sensitivity, the total masses of parent isotopes must be increased using enriched isotopes, and the backgrounds drastically decreased. A ton-scale ^{76}Ge experiment (with a possible common effort between GERDA and MAJORANA) [7], the full EXO experiment (nEXO [8]), and a possible upgrade of the CUORE experiment (CUPID, CUORE Upgrade with Particle IDentification [9,10]) are all designed to achieve this goal.

The advantage of the bolometric technique proposed for CUPID is not only the possibility to choose different DBD emitters combined with the capability of having a high resolution detector, but the realization of double-readout detectors in order to perform an active particle discrimination to reject the natural background. CUPID is presently in an R&D phase testing different type of crystals containing most of the interesting DBD emitters (^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te). The aim of CUPID, which will use the CUORE infrastructure once that experiment has concluded, is to increase the sensitivity to completely cover the inverted hierarchy region. In order to reach this goal, two major scientific milestones need to be reached:

1. increase the number of active DBD nuclei through development of bolometers made of enriched isotopes (as the experimental volume of the CUORE cryostat is fixed);
2. decrease the present natural radioactive background by two orders of magnitude by rejecting the major source of background for DBD bolometers due to α-particle interactions [11].

The initial idea to decrease the α-background in DBD bolometers was to use scintillating crystals [12] in which the discrimination between e/γ and α/neutron particles can be simply obtained with the additional readout of the scintillation light, through a second – very sensitive – bolometer working as a Light Detector (LD). Rather recently, however, after the observation of a very tiny light signal in a small TeO_2 bolometer [13], it was suggested [14] that particle discrimination could be obtained also in non-scintillating crystal bolometers (like TeO_2) by exploiting the Cherenkov light emission. Heavy α particles arising from natural radioactivity have velocities far below the threshold to emit Cherenkov photons in any kind of crystal. In the last four years several tests were performed on large [15–17] and very small [18,19] TeO_2 crystal samples coupled with different types of bolometric LDs. The challenge of this method is the detection of the extremely small amount of light emitted by electrons at the 0ν-DBD energy of ^{130}Te (2.53 MeV) that is of the order of $\approx$100 eV [20].

In this work we present for the first time the performance of *large enriched* TeO_2 in which the Cherenkov light is used for particle identification. This work demonstrates that $^{130}TeO_2$ can be a suitable candidate for the CUPID experiment in terms of energy resolution, internal radioactive contaminations and α-background discrimination.

2. Enriched crystal growth

The $^{130}TeO_2$ crystals used in this work were manufactured starting from enriched ^{130}Te in the form of metal powder, purchased from JSC Isotope, Russia.

The purity of the enriched material was certified as >99.9875%. The concentrations of the most troublesome metallic impurities were measured independently by ICP-MS and were found to be below 1 ppm, except for Fe (1.5 ppm), Cu (3.5 ppm) and Al (4.5 ppm). Radioactive ^{238}U and ^{232}Th were not observed, with a detection limit of the order of 5 ppt. The isotopic abundances of Tellurium in the powder, as measured by ICP-MS, are given in Table 1 and compared to the values reported by the vendor and the isotopic concentration of natural Tellurium [21]. The $^{130}TeO_2$ crystals were manufactured by Shanghai Institute of Ceramics of the Chinese Academy of Sciences (SICCAS), P.R. China, following basically the same technology as the one applied for the production of CUORE crystals [22]. Some specific procedures were applied though, in order to reduce the material losses which resulted in a $^{130}TeO_2$ powder synthesis efficiency $\geq$80%, and a crystal growth efficiency $\geq$90%, meaning an *irrecoverable* loss of 28%.[1] As shown in Table 2, the synthesis of the $^{130}TeO_2$ powder acts as a purification process reducing most of the metallic impurities to a concentration below 1 ppm.

Table 1
Concentration of the most abundant Tellurium isotopes in the metal used for the production of the crystals in this work. The errors on the measurements are of the order of 0.5% for the first two rows, and of the order of 10% for the other three.

Isotope	ICP-MS [%]	Certification [%]	Natural [%]
^{130}Te	92.26	92.13	34.08
^{128}Te	7.71	7.28	31.74
^{126}Te	0.015	0.02	18.84
^{125}Te	0.006	0.01	7.07
^{124}Te	0.0005	$\leq$0.005	4.74

Table 2
Concentration of the most problematic metallic impurities in enriched metal and in the $^{130}TeO_2$ powder used for the $^{130}TeO_2$ crystals growth. Last column: same values for a sample of natural TeO_2 powder.

Element	^{130}Te metal [*ppm*]	$^{130}TeO_2$ powder [*ppm*]	Nat. TeO_2 powder [*ppm*]
Cu	3.3	<0.19	<0.19
Pb	<0.017	<0.02	0.026
Al	4.4	3.4	<1.9
Fe	0.3	<0.2	1.0
Cr	<0.09	<0.09	0.15
Ni	<0.09	<0.09	0.09

A dedicated furnace and crucible system were built in order to cope with the relatively small amount of $^{130}TeO_2$ available and a *single*-growth cycle was applied instead of the double-growth process used for the production of CUORE crystals. This last point was adopted in order to decrease the amount of losses of the enriched material.

Also a dedicated temperature gradient and growth regime were applied in order to minimize any mass transfer between the seed (TeO_2 crystal with natural Te isotopic concentration) and the growing crystal. Preliminary tests were made using low enriched material as marker in order to make sure that the isotopic concentration of the feeding $^{130}TeO_2$ powder remains unchanged in the grown crystal (a detailed description of enriched $^{130}TeO_2$ crystal production will be given in a dedicated article). One single enriched crystal ingot was finally grown. Two crystals were produced out of the single ingot in order to study possible (radioactive) impurities segregation effects during crystal growth. The shapes of the two crystals were fixed by the requirement that the crystals be identical with the maximum total mass yield. Two $36\times38\times52$ mm^3 435 g crystals were cut and processed (shaped, chemical etched and polished) in a dedicated clean room with special precautions aimed at preventing possible radio-contamination of samples. In order to maximize the Cherenkov light output, four of the surfaces

[1] In an industrial dedicated synthesis and growing procedure these irrecoverable losses could be reduced.