Available online at www.sciencedirect.com
ScienceDirect
Physics Letters B 658 (2008) 193–197
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Search for 2β processes in ^{64}Zn with the help of $ZnWO_4$ crystal scintillator

P. Belli [a], R. Bernabei [a,*], F. Cappella [b], R. Cerulli [c], C.J. Dai [d], F.A. Danevich [e], B.V. Grinyov [f], A. Incicchitti [b], V.V. Kobychev [e], L.L. Nagornaya [f], S.S. Nagorny [e], F. Nozzoli [a], D.V. Poda [e], D. Prosperi [b], V.I. Tretyak [e], S.S. Yurchenko [e]

[a] *Dipartimento di Fisica, Università di Roma "Tor Vergata" and INFN, Sezione di Roma Tor Vergata, I-00133 Rome, Italy*
[b] *Dipartimento di Fisica, Università di Roma "La Sapienza" and INFN, Sezione di Roma, I-00185 Rome, Italy*
[c] *INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy*
[d] *IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China*
[e] *Institute for Nuclear Research, MSP 03680 Kyiv, Ukraine*
[f] *Institute for Scintillation Materials, 61001 Kharkiv, Ukraine*

Received 26 July 2007; received in revised form 26 October 2007; accepted 29 October 2007

Available online 17 November 2007

Editor: V. Metag

Abstract

Double beta processes in ^{64}Zn were searched for with the help of a low background $ZnWO_4$ crystal scintillator (mass of 117 g) at the Gran Sasso National Laboratories of the INFN. Total time of measurements was 1902 h. New improved half-life limits on different modes of double electron capture and electron capture with positron emission were established as: $T_{1/2}^{2\nu 2K} \geqslant 6.2 \times 10^{18}$ yr, $T_{1/2}^{0\nu 2K} \geqslant 4.0 \times 10^{18}$ yr, $T_{1/2}^{0\nu 2\varepsilon} \geqslant 3.4 \times 10^{18}$ yr, $T_{1/2}^{2\nu\varepsilon\beta^+} \geqslant 2.1 \times 10^{20}$ yr, and $T_{1/2}^{0\nu\varepsilon\beta^+} \geqslant 2.2 \times 10^{20}$ yr, all at 90% C.L.

PACS: 29.40.Mc; 23.40.-s

Keywords: Double beta decay; ^{64}Zn; $ZnWO_4$ crystal scintillators

1. Introduction

Neutrinoless (0ν) double beta (2β) decay is one of the low-energy effects which are forbidden in the Standard Model (SM) because of violation of the lepton number on 2 units, but it is naturally expected in many SM extensions [1]. It offers complementary information to that given by neutrino oscillation experiments; in fact, while oscillation experiments are sensitive to the neutrinos mass difference, the $0\nu 2\beta$ decay experiments can allow to test the lepton number non-conservation, to establish the nature of the neutrino (that is, if it is a Majorana particle, $\nu = \bar{\nu}$, or a Dirac particle, $\nu \neq \bar{\nu}$) and to give the absolute scale of the effective neutrino mass.

Experimental investigations in this field are concentrated mostly on $2\beta^-$ decays, processes with emission of two electrons. Developments in the experimental techniques during the last two decades lead to observation of two neutrino (2ν) $2\beta^-$ decay in 10 isotopes with half-lives in the range of 10^{18}–10^{21} yr, and to sensitivities on $0\nu 2\beta^-$ decays up to 10^{23}–10^{25} yr. Searches for $2\beta^+$ decays, processes with emission of two positrons (or $\varepsilon\beta^+$, electron capture with positron emission; or 2ε, capture of two electrons from atomic shells) are not so popular [2]. Reasons for such a situation, in particular, are: (1) in general, lower energy releases in $2\beta^+$ decays in comparison with those in $2\beta^-$ decays, that results in higher expected $T_{1/2}$ values; (2) usually lower natural abundances of $2\beta^+$ isotopes (which very often are lower than 1% with only few exceptions), that restrict the number of nuclei available for investigations. Nevertheless, studies of $2\beta^+/\varepsilon\beta^+/2\varepsilon$ decays are important because they could help to distinguish the mech-

* Corresponding author.
E-mail address: rita.bernabei@roma2.infn.it (R. Bernabei).

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2007.10.075

anism of neutrinoless 2β decay (i.e., if it is due either to the non-zero neutrino mass or to the right-handed admixtures in weak interactions) [3].

In addition to ^{64}Zn, which is a main subject of this Letter and will be discussed in detail later, experimental searches for $2\beta^+/\varepsilon\beta^+/2\varepsilon$ processes were recently performed for ^{74}Se [4], ^{78}Kr [5], ^{106}Cd [6], ^{120}Te [7]. The obtained experimental $T_{1/2}$ limits depend on the nucleus, but usually they are on the level of 10^{18}–10^{19} yr. Full list of results till 2002 can be found in [8] and more recent achievements in [1,2].

^{64}Zn is one of a few exceptions among $2\beta^+$ nuclei having a big natural isotopic abundance of 48.268% [9]. This feature allows either to build a large scale experiment without isotopical enrichment or to make this procedure less expensive. The mass difference between ^{64}Zn and ^{64}Ni nuclei is 1095.7(0.7) keV [10] and, therefore, double electron capture (2ε), and electron capture with emission of positron ($\varepsilon\beta^+$) are energetically allowed [8].

An intriguing situation with this nucleus exists since 1995, when a possible experimental indication of the $\varepsilon\beta^+$ decay of ^{64}Zn with $T_{1/2}^{(0\nu+2\nu)\varepsilon\beta^+} = (1.1 \pm 0.9) \times 10^{19}$ yr was suggested in Ref. [11]. A $\varnothing 7.6 \times 7.6$ cm NaI(Tl) scintillator and a 25% efficiency HP Ge detector, operating in coincidence, were used in that experiment. The excess of ≈ 85 events in the 511 keV peak was observed with a zinc sample (mass of 350 g, 392 h of exposure on the sea level), while no effect was detected without a sample or with copper or iron blanks.

For long time, sensitivities of other experiments were not enough to confirm or disprove the result of Ref. [11]. A CdZnTe semiconductor detector was used to search for 2β decays of ^{64}Zn in underground measurements performed in the Gran Sasso National Laboratories ($\simeq 3600$ m w.e.) over 1117 h in the COBRA experiment; however, the small mass of the detector (near 3 g) allowed to reach half-life limits at the level of 10^{16}–10^{17} yr [12]. These results were recently moderately improved with four CdZnTe crystals in the updated version of this experiment [13]. Low-background measurements with a small (4.5 g, 429 h of measurements) zinc tungstate ($ZnWO_4$) crystal scintillator was performed in the Solotvina Underground Laboratory ($\simeq 1000$ m w.e.) [14]; despite the low mass of the detector, limits at a level of 10^{18} yr were set in the latter experiment for 2β processes in ^{64}Zn.

First results of another recent experiment were reported in some conferences in 2003 and recently appear in [15]. HP Ge detector 456 cm^3 and CsI(Tl) $\simeq 400$ cm^3 were used in coincidence in measurements with 460 g Zn sample in the underground Cheong Pyung Laboratory ($\simeq 1000$ m w.e.). Measurements during 375 h gave the limit on $\varepsilon\beta^+$ decay of ^{64}Zn as: $T_{1/2}^{(0\nu+2\nu)\varepsilon\beta^+} > 1.3 \times 10^{20}$ yr [15].

The aim of the present work is to search for double beta decays in ^{64}Zn with higher sensitivity with the help of large $ZnWO_4$ scintillators. The main properties of $ZnWO_4$ scintillators are: (i) density equal to 7.8 g/cm^3; (ii) light yield $\simeq 13\%$ of that of NaI(Tl); (iii) refractive index equal to 2.1–2.2; (iv) emission maximum at 480 nm; (v) effective average decay time 24 µs. The material is non-hygroscopic and chemically inert; the melting point is at 1200 °C. Typical radiopurity of zinc tungstate crystals has been preliminarily investigated in [14]. As mentioned above, the present experiment has been carried out in the underground Gran Sasso National Laboratories of the INFN at a depth of $\simeq 3600$ m w.e.; data were collected over a period of 1902 h.

2. The experimental set-up

A clear, slightly colored $ZnWO_4$ crystal ($20 \times 19 \times 40$ mm, mass of 117 g), produced from monocrystal grown by the Czochralski method, was used in our experiment. The $ZnWO_4$ crystal was fixed inside a cavity of $\varnothing 47 \times 59$ mm in central part of a polystyrene light-guide 66 mm in diameter and 312 mm in length. The cavity was filled up with high-purity silicon oil. The light-guide was optically connected on opposite sides by an optical couplant to two low radioactive EMI9265–B53/FL 3″ diameter photomultipliers (PMT). The light-guide was wrapped by the PTFE reflection tape. Such an assembling with use of oil allowed to increase the light transmission from the scintillator to PMTs and to improve the energy resolution of the detector [16].

The detector has been installed deep underground in the low background DAMA/R&D set-up at the Gran Sasso Laboratory. It was surrounded by Cu bricks and sealed in a low radioactive air-tight Cu box continuously flushed with high purity nitrogen gas (stored deeply underground for a long time) to avoid the presence of residual environmental Radon. The Cu box has been surrounded by a passive shield made of 10 cm of high purity Cu, 15 cm of low radioactive lead, 1.5 mm of cadmium and 4 to 10 cm polyethylene/paraffin to reduce the external background. The whole shield has been closed inside a Plexiglas box, also continuously flushed by high purity nitrogen gas.

An event-by-event data acquisition system records the amplitude and the arrival time of events. Moreover, the sum of the signals from the PMTs was also recorded by a 1 GS/s 8 bit DC270 Transient Digitizer by Acqiris over a time window of 100 µs. To allow a good compromise to handle the data files and taking into account the slow scintillation decay of $ZnWO_4$, 20 MS/s sampling frequency was used during the data taking.

The time characteristics of $ZnWO_4$ scintillators under γ and α irradiation were studied in Ref. [14] with the help of a transient digitizer based on the 12 bit ADC (AD9022) operated at the sample rate of 20 MS/s. Three decay components $\tau_i \approx 0.7$, ≈ 7 and ≈ 25 µs with different amplitudes for γ rays and α particles were observed. These values offer the possibility to exploit in the production data the rejection of residual PMT noise[1] near a low energy threshold of $\simeq 15$ keV (see Fig. 1). This procedure eliminates some part of scintillation signals near energy threshold. The energy dependence of the detection efficiency was determined with the help of ^{133}Ba, ^{137}Cs, ^{228}Th and ^{241}Am radioactive sources. The measured efficiency ranges

[1] Time characteristics of PMT noise were studied in the $ZnWO_4$ set-up in a special run removing the scintillation crystal from the light-guide; more than one million noise events were recorded.