Title

TeO2 bolometers with Cherenkov signal tagging: towards next-generation neutrinoless double-beta decay experiments

Journal
European Physical Journal C, 75(1)

ISSN
1434-6044

Authors
Casali, N
Vignati, M
Beeman, JW
et al.

Publication Date
2015

DOI
10.1140/epjc/s10052-014-3225-4

Peer reviewed

Eur. Phys. J. C (2015) 75:12
DOI 10.1140/epjc/s10052-014-3225-4

THE EUROPEAN PHYSICAL JOURNAL C

Letter

TeO_2 bolometers with Cherenkov signal tagging: towards next-generation neutrinoless double-beta decay experiments

N. Casali[1,2], **M. Vignati**[3,4,a], **J.W. Beeman**[5], **F. Bellini**[3,4], **L. Cardani**[3,4], **I. Dafinei**[4], **S. Di Domizio**[6,7], **F. Ferroni**[3,4], **L. Gironi**[8,9], **S. Nagorny**[10], **F. Orio**[4], **L. Pattavina**[1], **G. Pessina**[8], **G. Piperno**[3,4], **S. Pirro**[1], **C. Rusconi**[8], **K. Schäffner**[1], **C. Tomei**[4]

[1] INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy
[2] Dipartimento di Scienze Fisiche e Chimiche, Università degli studi dell'Aquila, 67100 Coppito (AQ), Italy
[3] Dipartimento di Fisica, Sapienza Università di Roma, 00185 Rome, Italy
[4] INFN Sezione di Roma, P.le A. Moro 2, 00185 Rome, Italy
[5] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[6] INFN Sezione di Genova, 16146 Genoa, Italy
[7] Dipartimento di Fisica, Università di Genova, 16146 Genoa, Italy
[8] INFN Sezione di Milano Bicocca, 20126 Milan, Italy
[9] Dipartimento di Fisica, Università di Milano Bicocca, 20126 Milan, Italy
[10] INFN Gran Sasso Science Institute, 67100 L'Aquila, Italy

Received: 15 April 2014 / Accepted: 11 December 2014 / Published online: 14 January 2015

Abstract CUORE, an array of 988 TeO_2 bolometers, is about to be one of the most sensitive experiments searching for neutrinoless double-beta decay. Its sensitivity could be further improved by removing the background from α radioactivity. A few years ago it was pointed out that the signal from βs can be tagged by detecting the emitted Cherenkov light, which is not produced by αs. In this paper we confirm this possibility. For the first time we measured the Cherenkov light emitted by a CUORE crystal, and found it to be 100 eV at the Q-value of the decay. To completely reject the α background, we compute that one needs light detectors with baseline noise below 20 eV RMS, a value which is 3–4 times smaller than the average noise of the bolometric light detectors we are using. We point out that an improved light detector technology must be developed to obtain TeO_2 bolometric experiments able to probe the inverted hierarchy of neutrino masses.

1 Introduction

Neutrinoless double-beta decay ($0\nu\beta\beta$) is a process that violates the lepton number conservation law by two units, in which a parent nucleus decays into a daughter nucleus and emits two β particles. Unlike the process accompanied by the emission of two neutrinos, allowed by the Standard Model and observed in several nuclei, $0\nu\beta\beta$ has not yet been observed. Its discovery would reveal physics beyond the Standard Model: it would tell us that neutrinos, unlike all other elementary fermions, are Majorana particles, and would point to leptogenesis as the origin of the matter–antimatter asymmetry after the Big Bang (for a recent review see for example [1] and references therein). The experimental signature is very clear, a peak in the sum energy spectrum of the βs at the Q-value of the decay.

Bolometers proved to be good detectors to search for $0\nu\beta\beta$, thanks to the high variety of isotopes that can be studied, the excellent energy resolution, and the low background they can achieve. The CUORE experiment [2,3] will search for the $0\nu\beta\beta$ of ^{130}Te with an array of 988 TeO_2 bolometers, cryogenic calorimeters working at a temperature around 10 mK. Each bolometer weighs 750 g, for a total active mass of 741, 206 kg of which are ^{130}Te (34.2 % natural abundance [4] in tellurium). The energy resolution at the Q-value of the decay, 2,528 keV [5], is expected to be 5 keV FWHM. CUORE is under construction at Laboratory Nazionali del Gran Sasso (LNGS) in Italy, and it will start to take data in 2015.

The technology of TeO_2 bolometers has been demonstrated by Cuoricino, a 40 kg tower of 62 bolometers that, with 19.75 kg year of ^{130}Te data, set a lower limit to the decay half-life of 2.4×10^{24} years at 90 % C.L. [6]. The analysis of the data pointed out that the main source of background in the energy region of interest (ROI) for the $0\nu\beta\beta$ consisted in α particles generated by natural radioac-

[a] e-mail: marco.vignati@roma1.infn.it

tivity of the copper structure holding the crystals. To reduce it, the CUORE collaboration developed techniques to clean the copper and to assemble the detector in ultra radiopure environments. The success of this effort has recently been demonstrated by the CUORE-0 experiment, an array of 52 bolometers that reached an α background index of 0.019 ± 0.002 counts/(keV kg year), a factor 6 less than Cuoricino [7]. The background in CUORE, however, is still foreseen to be dominated by α particles, limiting the sensitivity to the $0\nu\beta\beta$ half-life to around 10^{26} years in 5 years of data taking. This corresponds to an effective neutrino Majorana mass that ranges, depending on the choice of the nuclear matrix element, from 40 to 100 meV, values that are quite far from covering the entire interval of masses corresponding to the inverted hierarchy scenario, that ranges from 10 to 50 meV [1].

The background can be reduced by detecting the small amount of Cherenkov light that is emitted by interacting particles in TeO_2 crystals. In fact, at the energy scale of interest for $0\nu\beta\beta$, the βs (signal) are above threshold for Cherenkov emission, while α particles (background) are not [8]. In a previous paper [9] we operated a 117 g TeO_2 bolometer surrounded by a 3M VM2002 reflecting foil, monitoring a crystal face with a germanium bolometer acting as light detector. In coincidence with the heat released in the TeO_2 we were able to detect the light emitted by β/γ particles, which amounted to 173 eV at 2,528 keV. The crystal was doped with natural samarium, which contains ^{147}Sm, an α-unstable isotope with $Q = 2310$ keV. The light detected from these decays was compatible with zero, confirming that at the $0\nu\beta\beta$ energy scale no light is emitted by αs. Finally, room temperature tests confirmed that the light emitted by particles interacting in TeO_2 can be ascribed to the sole Cherenkov emission, excluding a contribution from the scintillation [10].

In this paper we present the results of a test conducted on a CUORE bolometer, i.e. a 750 g crystal, 6 times larger than that used in our previous work and without samarium doping. The results confirm that the α discrimination in CUORE is possible, but the light signal is small and requires light detectors with higher sensitivity than that provided by bolometers.

2 Experimental setup

The TeO_2 crystal comes from samples of the CUORE batches used to check the radiopurity and the bolometric performances during the production [11], and therefore is identical to the crystals that are currently being mounted in CUORE. The crystal is a $5 \times 5 \times 5$ cm^3 cube with translucent faces, two opposite of which have a better polishing quality, close to optical polishing grade. All faces are surrounded by the VM2002 light reflector except for an optical one that is monitored by a 5 cm in diameter, 300 µm thick germanium light

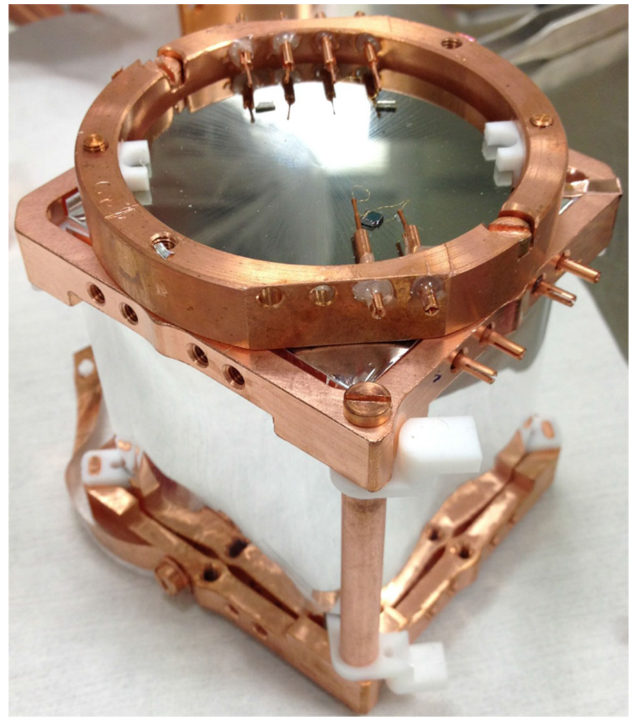

Fig. 1 The TeO_2 crystal in the copper holder, surrounded by a 3M VM2002 light reflector and monitored by the germanium bolometric light detector

detector (LD) [12] (Fig. 1). Both the TeO_2 crystal and the germanium are operated as bolometers, using a neutron transmutation doped germanium (NTD-Ge) thermistor as temperature sensor [13]. The detectors are held in a copper structure by means of teflon (PTFE) supports, anchored to the mixing chamber of a dilution refrigerator. The setup is operated in the CUORE/LUCIFER R&D cryostat, in Hall C of LNGS [14].

As in Ref. [9], the read-out of the thermistor is performed using the Cuoricino electronics [15]. The analog signals are filtered by 6-pole active Bessel filters [16] and then fed into an 18-bit National Instrument PXI analog-to-digital converter (ADC), the same system being used in CUORE-0. The filter cutoff and the ADC sampling frequency are set to 12 Hz and 125 Hz for the TeO_2, respectively, and to 120 Hz and 2,000 Hz for the LD, respectively. The trigger is software generated on each bolometer. When it fires, waveforms 5 s long on the TeO_2 and 250 ms long on the LD are saved on disk. Additionally, when the trigger fires on the TeO_2, the waveform on the LD is acquired irrespective of its own trigger.

To maximize the signal to noise ratio, the waveforms are processed offline with the optimum filter algorithm [17,18]. On the TeO_2 the pulse is identified with a peak finder algorithm, and the amplitude is evaluated as the maximum of the peak. On the LD, to eliminate noise artifacts at the threshold, the pulse amplitude is evaluated at the characteristic time delay of the LD response with respect to the pulse on the

TeO_2, which is estimated in calibration runs using events generated by particles interacting in both detectors (for more details see Ref. [19]).

The light detector is exposed to a permanent ^{55}Fe source, providing 5.9 and 6.5 keV calibration X-rays. The typical rise and decay times of the pulses are 2.6 and 6 ms, respectively, while the energy resolution at the iron peaks and at the baseline is 135 and 72 eV RMS, respectively. To calibrate the TeO_2 and to generate events in the $0\nu\beta\beta$ region, the setup is illuminated by a ^{232}Th source placed outside the cryostat. The rise and decay times of the TeO_2 pulses are 40 and 532 ms, respectively, values that are similar to the CUORE-0 ones [7].

The energy resolution at the 2615 keV ^{208}Tl peak from the thorium source is 11.5 keV FWHM, worse than the 5.7 keV FWHM obtained averaging all the CUORE-0 bolometers. This might be due to the different working temperature, which was chosen higher than in CUORE-0 (20 mK instead of 10 mK) in order to improve the energy resolution of the light detector (see Ref. [12] for details). The worse energy resolution of the TeO_2 bolometer does not affect our results, since attention is focused on the light signal.

3 Results

The energy spectrum acquired from the TeO_2 bolometer in 6.86 days of data taking is shown in Fig. 2. The peak around 5400 keV is due to the α-decay of ^{210}Po, a natural contamination of the TeO_2 crystal observed also in the 117 g detector and in CUORE-0. The remaining peaks are γs from the ^{232}Th source, except for the peak at 1,461 keV, which is a γ from ^{40}K contamination of the cryostat. Both the single escape (SE) and the double escape (DE) peaks of the 2615 keV γ from ^{208}Tl are visible. The presence of the DE peak is of particular interest because it is a single site production of a e^- and of a e^+, a process similar to the $0\nu\beta\beta$.

The light detected versus calibrated heat in the TeO_2 crystal is shown in Fig. 3. The distribution of the light corresponding to each peak in Fig. 2 (blue dots in the figure) is fitted with a Gaussian, the mean of which is overlaid onto the figure. The mean light from the α-decay of ^{210}Po is found to be $\langle L_\alpha \rangle = -3.9 \pm 14.5$ eV, i.e. compatible with zero. The mean light from the γ peaks is fitted with a line $\langle L_{\beta/\gamma} \rangle = \mathrm{LY} \times (\mathrm{energy} - E_{\mathrm{th}})$, with $E_{\mathrm{th}} = 280 \pm 60$ keV and $\mathrm{LY} = 45 \pm 2$ eV/MeV. The standard deviations of the light distributions are found compatible with the baseline noise of the LD, which therefore appears as the dominant source of fluctuation, hiding any possible dependence on the position of the interaction in the TeO_2 crystal or statistical fluctuations of the number of photons. As in our previous work, the light from the DE peak is compatible with the light from γs, indicating that the fitted line can be used to predict the amount of light detectable from $0\nu\beta\beta$ events. We compute 101.4 ± 3.4 eV of light for a β/γ event with $0\nu\beta\beta$ energy, 72 eV less than the light detected at the same energy in the 117 g detector.

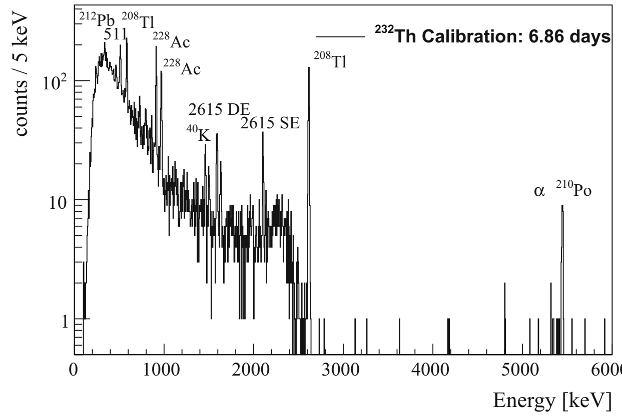

Fig. 2 Energy spectrum acquired by the TeO_2 crystal. All the labeled peaks are γs, except for the single and double escape peaks of the 2615 keV γ from ^{208}Tl, which are $e^- + e^+ + \gamma$ and $e^- + e^+$ events, respectively, and for the events around 5.4 MeV, which are generated by the α-decay of ^{210}Po in the crystal

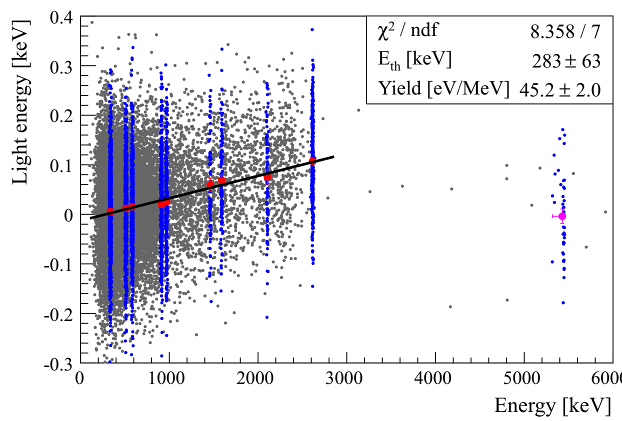

Fig. 3 (Color online) Detected light versus calibrated heat in the TeO_2 bolometer for all the acquired events (*gray*) and for the events belonging to the peaks labeled in Fig 2 (*blue*). The mean light is clearly energy dependent for the γ peaks (*red circles* below 3 MeV) and compatible with zero for the α-decay of the ^{210}Po (*pink circle* at 5.4 MeV)

The detected light at the $0\nu\beta\beta$ is small, at the same level of the LD noise, and does not allow one to perform an event by event rejection of the α background. As indicated in Ref. [8], the emitted Cherenkov light amounts to several hundreds of eV, a much higher value than what we detect.

To increase the light collection efficiency, we applied various modifications to the setup:

1. We changed the VM 2002 light reflector to aluminum foils. Aluminum is expected to have higher reflectivity in the UV band, the region where the Cherenkov emission is

more intense. Nevertheless, the amount of light detected is 25 % less than in the case of VM 2002.

2. We removed the VM 2002, which is a specular light reflector, and wrapped the crystal with teflon tape, which is a light diffusor. The amount of light detected is compatible with the VM 2002 measurement.
3. We changed the LD to an identical one, but we coated the side faced to the TeO_2 with 60 nm of SiO_2. It has been demonstrated, in fact, that in the red/infrared band this layer enhances the light absorption by up to 20 % [20,21]. In our application, however, the amount of light detected does not change significantly.
4. We added a second LD, monitoring opposite faces with two different light detectors. The amount of light detected from each LD is found to be the 50 % of the amount detected with a single LD. This causes an overall decrease of the signal to noise ratio, because each LD adds its own noise.
5. We replaced the crystal with a cylindrical one, 4 cm in diameter and in height. Again the amount of light detected does not change.

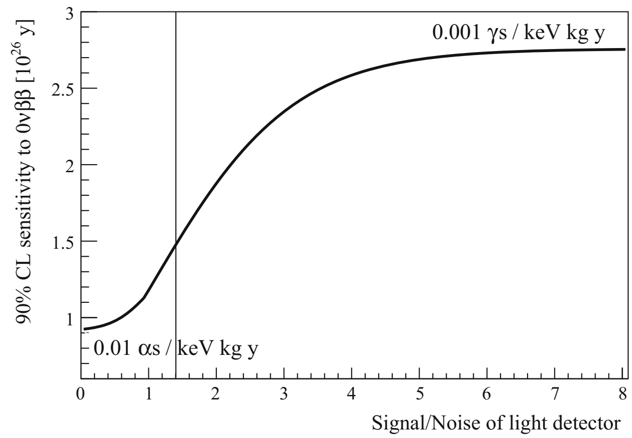

Fig. 4 90 % C.L. sensitivity to the half-life of ^{130}Te as a function of the signal to noise ratio of the light detectors, under the reasonable hypothesis of an α background index in CUORE of 0.01 counts/(keV kg year). The sensitivity of the experiment without light detectors corresponds to S/N = 0. When S/N > 5 the α background is hidden by the irreducible background predicted from γ interactions, amounting to 0.001 counts/(keV kg year), and the sensitivity is maximal. The performance of the light detectors used in this work, S/N = 1.4, is clearly too low

Summarizing, none of the above trials succeeded in providing a significant increase of the light collection efficiency, indicating that most of the light is absorbed by the TeO_2 crystal. This is due to the high refractive index of the TeO_2 crystal ($n \sim 2.4$ [22]): many photons are reflected internally several times up to absorption. This effect is confirmed by the higher light yield obtained with the small (117 g) crystal and by preliminary results from simulations of the light collection.

The setup providing the highest light signal, around 100 eV at the $0\nu\beta\beta$, consists in a single LD with the crystal surrounded by the VM 2002 reflector or wrapped with teflon tape.

4 Perspectives

The recent CUORE-0 result restricted the prediction of the amount of α background in CUORE from $B_\alpha = 0.01 - 0.04$ to $B_\alpha = 0.01$ counts/(keV kg year) [7], while the ultimate source of background, due to β/γ radioactivity from the setup, still amounts to $B_{\beta/\gamma} = 0.001$ counts/(keV kg year). From these numbers and from the specs of CUORE we perform toy Monte Carlo simulations to estimate the 90 % C.L. sensitivity of CUORE equipped with light detectors.

The outcome of a toy experiment is fitted in energy with a flat probability density function (pdf) for the background and a Gaussian pdf for the signal, and is simultaneously fitted in light with Gaussians pdfs for the α and β/γ light distributions. The posterior pdf of the signal events is obtained integrating over the nuisance parameters and assuming a flat prior. The sensitivity of a single experiment (N_{90}) is computed as the number of signal events corresponding to the 90 % of the posterior cumulative distribution. Several (∼3,000) experiments are generated, and the median of N_{90} is used as estimator of the sensitivity. The entire procedure is repeated while varying the signal to noise ratio in the light detector (Fig. 4).

From the figure one sees that the application of light detectors to CUORE would increase its 90 % C.L. sensitivity to the half-life of ^{130}Te to 2.7×10^{26} years, a factor 3 higher than CUORE without light detectors. To achieve this goal one needs a signal to noise ratio in the light detector greater than 5, a value that is far from that featured by the setup in this work, equal to $101/72 = 1.4$ eV/eV.

From the results presented the increase of the light signal is difficult, and therefore to upgrade CUORE light detectors able to provide a noise level below 20 eV RMS are needed. Other than trying to improve the NTD technology, there are at least two possible alternatives. The use of phonon-mediated transition edge sensors (TES), as in the CRESST dark matter experiment [23], or the use of phonon-mediated kinetic inductance detectors (KID), as recently proposed in Ref. [24]. The TES technology has already proved to reach very good noise levels, but the implementation of 988 light detectors implies a complicated read-out, mainly because of the cryogenic SQUID amplifiers that are employed. KIDs already proved to be a highly multiplexable technology in astrophysical applications (up to 400 channels on the same read-out line [25]) but the required energy resolution in our application still needs to be demonstrated.

5 Conclusions

We tested the possibility to discriminate the α background in CUORE by tagging the signal from β particles through the detection of Cherenkov light. The detected light at the ^{130}Te Q-value is around 100 eV for β/γ particles and no light is detected from α interactions, confirming the validity of this technology. However, the signal is small at the same level of the noise of the bolometric light detectors we are using, and does not allow us to perform an event by event discrimination of the background. We tested modifications of the setup, by using different light reflectors or multiple light detectors, but the light yield did not increase.

We are working on simulations to estimate the fraction of emitted light that escapes the crystal and is eventually absorbed by the light detector. Critical parameters are the index of refraction and the absorbance of TeO_2, which unfortunately are not available in the literature for low temperatures. To this end we are setting up a dedicated measurement.

Given the results obtained so far, we conclude that, to remove completely the α background in CUORE, light detectors with a noise of 20 eV RMS are needed, a factor 3–4 times better than the bolometric light detectors we used in this work. Changing the technology to TES or KID devices could be an alternative, provided that the present read-out and sensitivity limits are overcome.

CUORE without α background would reach a 90 % C.L. sensitivity to the $0\nu\beta\beta$ half-life of more than 3×10^{26} years, a factor 3 better than the upcoming experiment. Combining the light read-out with an enrichment in ^{130}Te from the natural 34 to ∼90 % would push the half-life sensitivity by another factor ∼3. Depending on the choice of the nuclear matrix elements, this corresponds to an effective neutrino mass sensitivity in the range 14–35 meV, down into the inverted hierarchy of neutrino masses.

Acknowledgments The authors thank the CUORE collaboration for providing the TeO_2 crystal. This work was supported by the European Research Council (FP7/2007–2013) under contract LUCIFER no. 247115 and by the Italian Ministry of Research under the PRIN 2010–2011 contract no. 2010ZXAZK9.

References

1. S. Bilenky, C. Giunti, Mod. Phys. Lett. **A27**, 1230015 (2012)
2. C. Arnaboldi et al., Nucl. Instrum. Meth. **A518**, 775 (2004)
3. D. Artusa et al. (2014, submitted)
4. M.A. Fehr, M. Rehkämper, A.N. Halliday, Int. J. Mass Spectrom. **232**(1), 83 (2004). doi:10.1016/j.ijms.2003.11.006. http://www.sciencedirect.com/science/article/pii/S1387380603004494
5. M. Redshaw, B.J. Mount, E.G. Myers, F.T. Avignone, Phys. Rev. Lett. **102**, 212502 (2009). doi:10.1103/PhysRevLett.102.212502
6. E. Andreotti et al., Astropart. Phys. **34**, 822 (2011). doi:10.1016/j.astropartphys.2011.02.002
7. C. Aguirre et al. (2014, submitted)
8. T. Tabarelli de Fatis, Eur. Phys. J. C **65**, 359 (2010). doi:10.1140/epjc/s10052-009-1207-8
9. J. Beeman et al., Astropart. Phys. **35**, 558 (2012). doi:10.1016/j.astropartphys.2011.12.004
10. N. Casali, F. Bellini, I. Dafinei, M. Marafini, S. Morganti et al., Nucl. Instrum. Meth. A **732**, 338 (2013). doi:10.1016/j.nima.2013.07.024
11. F. Alessandria et al., Astropart. Phys. **35**, 839 (2012). doi:10.1016/j.astropartphys.2012.02.008
12. J. Beeman et al., JINST **8**, P07021 (2013). doi:10.1088/1748-0221/8/07/P07021
13. K.M. Itoh et al., Appl. Phys. Lett. **64**, 2121 (1994)
14. S. Pirro, Nucl. Instrum. Meth. A **559**, 672 (2006). doi:10.1016/j.nima.2005.12.197
15. C. Arnaboldi et al., Nucl. Instrum. Meth. A **520**, 578 (2004). doi:10.1016/j.nima.2003.11.319
16. C. Arnaboldi, M. Cariello, S. Di Domizio, A. Giachero, G. Pessina, Nucl. Instrum. Meth. A **617**, 327 (2010). doi:10.1016/j.nima.2009.09.023
17. V. Radeka, N. Karlovac, Nucl. Instrum. Methods **52**, 86 (1967)
18. E. Gatti, P.F. Manfredi, Riv. Nuovo Cimento **9**, 1 (1986)
19. G. Piperno, S. Pirro, M. Vignati, JINST **6**, P10005 (2011). doi:10.1088/1748-0221/6/10/P10005
20. J. Beeman et al., Nucl. Instrum. Meth. A **709**, 22 (2013). doi:10.1016/j.nima.2013.01.019
21. J. Beeman et al., JINST **8**, P05021 (2013)
22. N. Uchida, Phys. Rev. B **4**, 3736 (1971). doi:10.1103/PhysRevB.4.3736. http://link.aps.org/doi/10.1103/PhysRevB.4.3736
23. G. Angloher et al., Eur. Phys. J. **C72**, 1971 (2012). doi:10.1140/epjc/s10052-012-1971-8
24. S. Di Domizio et al., J. Low Temp. Phys. (2014, in publication). doi:10.1007/s10909-013-1076-2
25. O. Bourrion, C. Vescovi, J. Bouly, A. Benoit, M. Calvo et al., JINST **7**, P07014 (2012). doi:10.1088/1748-0221/7/07/P07014