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Preliminary results on double beta decay of ^{130}Te with an array of twenty cryogenic detectors

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Abstract

Preliminary results on double beta decay of ^{130}Te obtained in the first run of an array of twenty cryogenic detectors are presented. The set-up is made with crystals of TeO_2 of 340 grams each corresponding to the largest presently operating cryogenic mass. It was run under a heavy shield in the Gran Sasso Underground Laboratory at a depth of about 3500 m.w.e. By recording the pulses of each detector in anticoincidence with the others a 90% c.l. lower limit of 5.6×10^{22} years has been obtained on the lifetime for neutrinoless double beta decay of ^{130}Te in a preliminary test run, corresponding to about one week of effective running time. No evidence is also found for double beta decay to the first excited 2^+ state of ^{130}Xe with a 90% c.l. lower limit of 1.7×10^{22} years on that lifetime. Some consequences of the present results in the interpretation of geochemical experiments are discussed.

1. Introduction

An intense theoretical and experimental activity has been devoted in the recent years to the study of double beta decay [1–4]. This process consists in the spontaneous and simultaneous emission of two electrons from a nucleus (A,Z) and, despite its predicted low rate, can be revealed if single beta decay to the nucleus (A,Z + 1) is energetically forbidden or at least strongly hindered by a large change of angular momentum. Two-neutrino double beta decay, where two antineutrinos are emitted together with the two electrons, converses the lepton number and is predicted by the standard weak interaction theory. It has been found, or at least indicated, for ten nuclei [1–7]. The measured lifetimes do not disagree with theoretical calculations if the large differences among these predictions, sometimes extending to two orders of magnitude, are taken into account. If lepton number is violated, the two electrons could be emitted without any other particle. This process, commonly called neutrinoless double beta decay, would have obvious implications in the field of Gran Unified or Supersymmetric theories [1,3,6–9]. Its rate would be in principle enhanced by much larger available phase space and the two electrons would share the total

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transition energy, since the recoil energy of the daughter nucleus is negligible. The spectrum of the sum of the two electron energies would therefore show a peak corresponding to the transition energy. A third lepton violating double beta decay process where a massless Goldstone boson, named majoron, would be emitted together with the two electrons will not be considered here.

Experimentally double beta decay has been searched for with *indirect* method [1,2] like the *milking* technique, where a large mass of the parent nucleus is stored underground to produce a sizable amount of the daughter one. In *geochemical* experiments, which are particularly relevant for tellurium, a rock containing a large amount of the nucleus (A,Z) is isotopically analyzed for the presence of the daughter nucleus (A,Z + 2). Evidence for double beta decay of ^{82}Se, ^{128}Te, ^{130}Te and possibly ^{96}Zr has been obtained in this way. The possibility that in the first three cases the daughter atoms are in gas form could have escaped since the formation of the rock, thus indicating a lower double beta decay rate, has been thoroughly studied [10–13]. On the other side the possibility that interactions of cosmic rays in tellurium could have produced the nuclei ^{128}Xe, ^{130}Xe which could therefore mimic double beta decay have been investigated by bombarding with protons natural Te targets [14]. This effect does not seem to be large and has been taken into account in the latest experiments. The geochemical results on double beta decay of ^{82}Se are in good agreement among themselves and with the value obtained in direct experiments [1,2]. There is on the contrary disagreements among the results for double beta decay of ^{128}Te, with lifetimes ranging from $(1.5 \pm .2) \times 10^{24}$ to $(7.7 \pm .4) \times 10^{24}$ years, and of ^{130}Te with lifetimes from $(7.5 \pm .3) \times 10^{20}$ to $(2.7 \pm .1) \times 10^{21}$ years. The ratio of lifetimes for the decay of ^{128}Te and ^{130}Te is less critical and it has been used to extract a value for neutrinoless double beta decay. This approach is however based on the rather questionable hypothesis that the matrix elements for the decays of these two isotopes are the same. One has to note in addition that the production of the daughter isotope in geochemical experiments is obviously the result of all possible double beta decay processes including two neutrino and neutrinoless double beta decay to the excited states of the daughter nucleus. The case of ^{130}Te has been recently studied by M. Aunola and J. Suhonen [15]. According to these authors the nuclear matrix elements for two neutrino double beta decay to an excited 0^+ level around 1100–1200 keV could be two orders of magnitude larger than for the corresponding transition to the ground level. This could lead to an enhancement factor on the rate such to compensate the much lower available phase space.

In many of the *direct* experiments the two electrons emitted by a *passive* source are revealed and measured. Conversely in the *source = detector* approach [16] the source is *active* and acts as detector. Experiments of this type have been carried out with scintillators, proportional and time projection chambers and semiconductors [1–7].

The use of cryogenic detectors to search for double beta decay has been suggested in 1984 [17]. These detectors [18] are based on the fact that the heat capacity at low temperatures of a diamagnetic and dielectric crystal is proportional to the cube of the ratio between the operating and Debye temperatures. As a consequence it can become so small that even the tiny energy released by a particle in form of heat can be revealed by the increase of temperature of the absorber. This can be measured by a sensor in thermal contact with it. Unlike the conventional detectors, the cryogenic ones allow an ample choice of double beta decay candidates, the only requirement being that they form a compound which can be grown in the form of a dielectric and diamagnetic crystal with a reasonable Debye temperature.

^{130}Te looks an excellent candidate to searches on double beta decay due to its high transition energy (2528.8 ± 1.3 keV) [19], and large abundance (33.8%) [20] which allows to perform a sensitive experiment even with natural tellurium. In addition the expected signal at 2528 keV is in an energy region between the peak and the Compton edge of the ^{208}Tl γ-rays at 2615 keV, which produce most of the background in this high energy region. Results on neutrinoless double beta decay of ^{130}Te have been already obtained with a single detector [21] and with an array of four detectors made by 340 g crystals of TeO_2 [22]. We report here the first operation and the preliminary results of an array of 20 crystals of 340 g each, which represents at present by far the largest cryogenic detecting system. The oper-

ation of the detectors in coincidence and anticoincidence, already adopted by us for the first time with thermal detectors [23–25] could allow extracting significant limits on the lifetime of Te neutrinoless double beta decay.

2. Experimental details

The array (Fig. 1) consists in a tower with five floors of 4 detectors, operating in a dilution refrigerator in Gran Sasso Underground Laboratory [26]. The twenty absorbers are crystals of natural TeO_2 of $3 \times 3 \times 6\,cm^3$ with a total active mass of about 6.8 kg. The tower frame is made of previously tested low radioactivity Oxygen Free High Conductivity (OFHC) Copper, soldered with an electron beam after accurate polishing in order to avoid radioactive contamination. The crystals are fastened to this structure by means of PTFE supports. The temperature sensors are Neutron Transmutation Doped Ge thermistors provided to us by prof. E. Haller, specifically prepared in order to present similar thermal characteristics, and thermally coupled to each crystal with six 0.6 mm diameter glue spots. A resistor of 10 to 100 kΩ, realized with a heavily doped meander on a 1 mm^3 silicon chip, was attached to each absorber and acted as a heater to calibrate and stabilize the gain of the bolometer [27].

The tower is connected via an OFHC copper cold finger to the mixing chamber of a dilution refrigerator specially constructed with previously tested low radioactivity materials. The entire set-up is shielded with two layers of lead of 10 cm minimum thickness each. The outer one is made of common low radioactivity lead, the inner of special lead with contamination of 16 ± 4 Bq/kg in ^{210}Pb. The electrolytic copper of the thermal shields of the refrigerator provides an additional shield of minimum thickness of 2 cm. The intrinsic and unavoidable radioactivity of the dilution unit (e.g. from silver and stainless steel) is shielded by a layer of 10 cm Roman lead framed *inside the cryostat* immediately above the tower of the array. Recent measurements [28] have shown that the ^{210}Pb activity in this lead is less than 4 mBq/kg. The refrigerator is surrounded by a Plexiglas anti-radon box by a Faraday cage to eliminate the electromagnetic interferences.

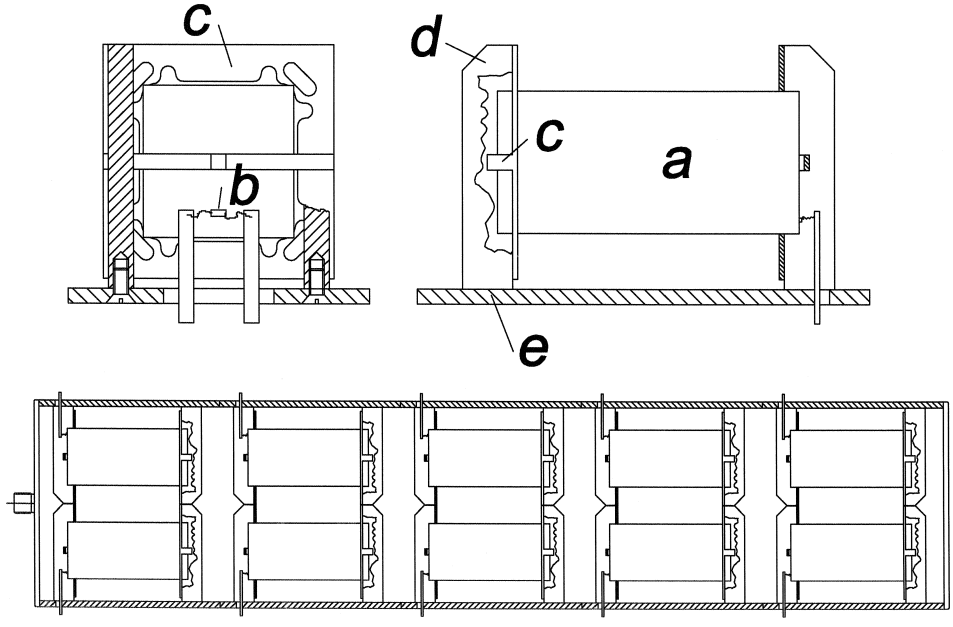

Fig. 1. Scheme of the array of twenty detectors, with top and lateral section of a single module assembly: a. crystal; b. thermistor; c. PTFE frame; d. copper bar; e. copper plate.

The 60 μm diameter constantan read-out wires are connected to the thermistors and go from room temperature to the mixing chamber passing through five thermalizing stages. While each detector is read independently by a twisted pair of wires, the heaters are connected in parallel, in groups of five, along the tower walls. The front end read out (preamplifier, filters and the detector bias circuits) are at room temperature. A low noise voltage sensitive preamplifier was used to read the detector signals. The differential configuration reported in [29] allows minimizing cross-talk and microphonic effects of the connecting wires. Parasitic capacitance due to the length of the connecting wires produce a negligible integration, since the detector signal bandwidth extends up to a few Hz. A further amplifying stage and a 4 pole antialiasing Bessel filter complete the analog link. The signal is acquired by 8 channel 16bit ADC embedded in a VXI acquisition system, expandable through a multiplexer to 32 channels. The data analysis is completely performed off-line. The detector bias voltage is derived by 20 independent symmetric bias circuits, all fed by an external filtered voltage supply, using a pair of 10 GΩ load resistances located at room temperature.

The array was cooled down to temperatures around 8 mK. A spread in the detector base temperatures around 1 mK observed, which we consider reasonable if the non perfect reproducibility of the detector modules is taken into account. To optimize the detector energy resolution the mixing chamber had to be *slightly heated* to about 10 mK. At the optimum bias point the operating temperature of each detector ranges from 11.5 to 14 mK. In these conditions the thermal responses of the detectors varied from 100 to 340 μV/MeV, due to differences in thermistor sensitivity and detector mounting. The base line resolution ranges from 2.5 to 3.5 keV FWHM.

The 20 detectors were calibrated by a single radioactive source of ^{232}Th. The corresponding spectra, presented in Fig. 2, show the excellent reproducibility of the array. The FWHM energy resolu-

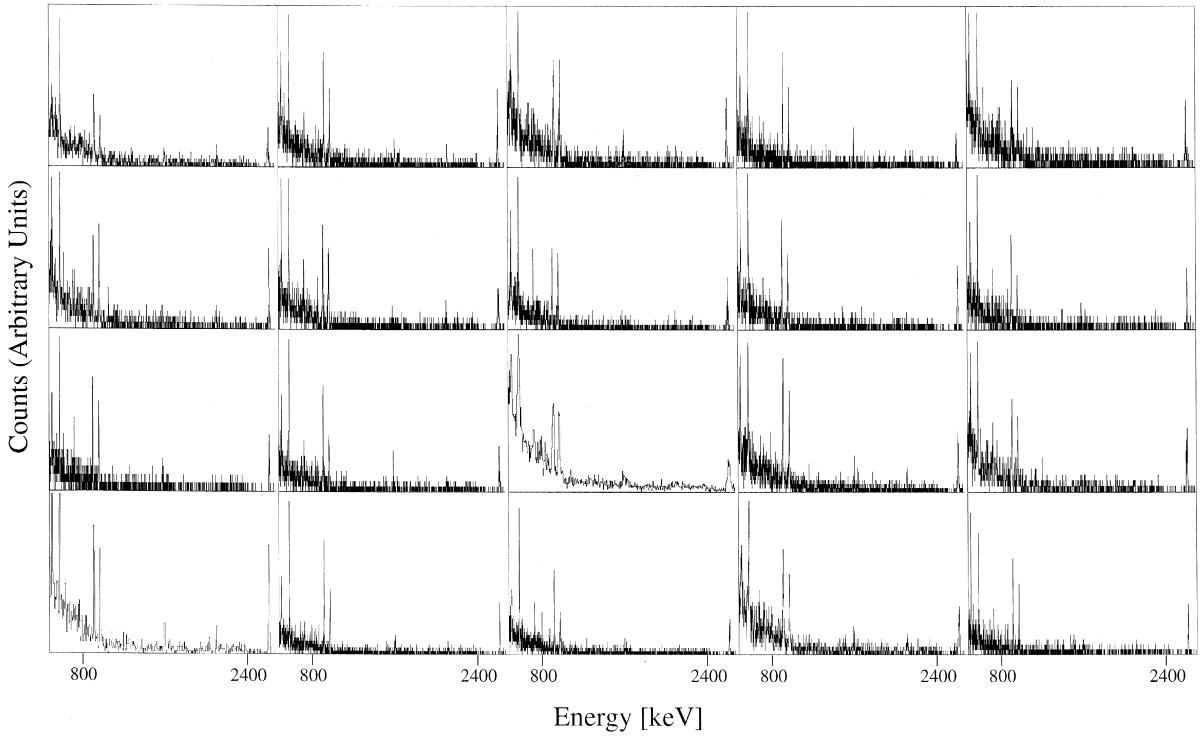

Fig. 2. Spectra obtained with the twenty detectors exposed to a single source of ^{232}Th.

tions at the 2615 keV ^{208}Tl line range from 4 to 10 keV in this preliminary test run.

3. Experimental results

Only a part of the read-out electronics was ready for this preliminary run which was intended to test the overall performance of the array. As a consequence only eight channels could be read out simultaneously. A test measurement to check the overall performance of the array was therefore carried out for slightly more than a month. The measurement is presently stopped to further clean the detectors against residual radioactive contamination, to optimize their thermal performance, to complete the electronic read out and to install a further internal lateral shield of Roman lead to reduce the background in the low energy region. A preliminary search on neutrinoless double beta decay was carried out combining the pulses from eight detectors laying on the same face (Fig. 1), five in one column and three on the other. This search, corresponding to only ''4537 hours *x* detector'' of effective running time, yields already significant results that considerably overcome those obtained by us in the previous experiments. A spectrum has been obtained by operating each of the detectors in anticoincidence with all the other seven and by adding the corresponding eight spectra. Due to the limited number of instrumented detectors this anticoincidence only reduces the event rate by slightly more than 10%.

In the region below 2000 keV we could see the lines at 144, 295, 352, 609, 1120, 1238 and 1764 keV due to the U chains and the peak a 511 keV. Only an indication at 239, 583, 911 and 968 keV was found in this region for peaks of the ^{232}Th chain. We also found lines at 1173 and at 1332 keV due to ^{60}Co and at 1461 keV due to ^{40}K. In addition there are lines at 89 and 248 keV and an excess activity in the line at 144 keV. We attribute them to contamination of ^{123m}Te, ^{125m}Te and ^{127m}Te produced by activation of tellurium from cosmic ray neutrons during the transport from the factory of production to our underground laboratory. An improved analysis of all these contaminations, also in view of searches for direct interactions of WIMPS, will be performed using the coincidence-anticoincidence method when the entire array will be fully in operation.

The spectrum in the region above 2000 keV (Fig. 3) shows the lines at 2204 and 2447 keV (^{214}Bi) and at 2615 keV (^{208}Tl), which confirms the reproducibility of the array. The counting rate in the last peak, which is relevant in our search for neutrinoless double beta decay, is reduced by an order magnitude with respect to our previous experiments [21,22] due to the increased thickness of the external layer of lead and the use of less contaminated materials for the mechanical support of the detectors. No event appears in the wide region around 2528 keV, which is scarcely populated, as pointed out before, being between the peak of ^{206}Tl, its Compton edge and the ^{214}Bi line at 2447 keV. By applying the usual maximum likelihood procedure and taking into account our Monte Carlo evaluated 83.14% detection efficiency, we can set at 90% confidence level a lower limit of 5.6×10^{22} years on the half life for neutrinoless double beta decay of ^{130}Te. This limit, achieved in slightly more than a week of effective running time, is by far the most restrictive in the literature and three times larger than the one obtained in our previous experiment which lasted more than one year with a single detector.

No peak appears at the energy of 867 keV corresponding to neutrinoless double beta decay of ^{128}Te, where however some background counts are present. With the same likelihood method we can set at 90% confidence level a much less significant upper limit

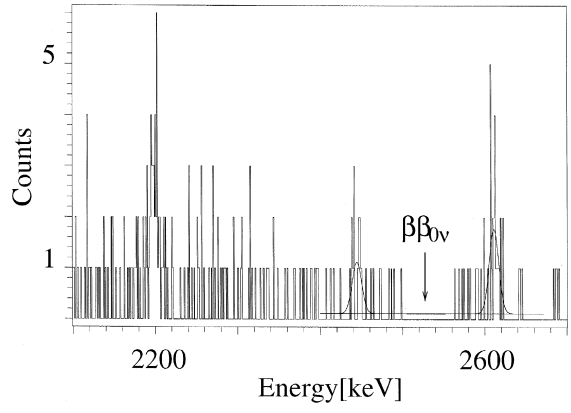

Fig. 3. Combined spectrum in the region of neutrinoless double beta decay of ^{130}Te.

of 1.7×10^{22} years for the lifetime of this neutrinoless double beta decay.

4. Comparison with geochemical experiments

Our present background in the low energy region does not allow yielding a lifetime for two-neutrino double beta decay of ^{130}Te to the ground level which could be compared with the values obtained in geochemical experiments. The present experiment allows however to set limits on the individual neutrinoless double beta decay modes. Our limit on neutrinoless double beta decay to the ground state of ^{130}Xe already excludes contributions of 1.3 to 4.8% to the overall rate in the two extreme results of Manuel [10] and Bernatovitz [12], respectively. The geochemical evidence for double beta decay can also be the result of decays to the 2^+ excited state of ^{130}Xe at 536 keV. We have therefore considered the sum spectrum recorded *without the anticoincidence cut* and found no evidence for the peak at 1992 keV expected for this decay. With a maximum likelihood procedure and by calculating with a Monte Carlo method the probability that the two electrons are captured in one detector and the 536 keV γ-ray escapes from it we obtain at 90% c.l. a lower limit of 5×10^{21} years for this neutrinoless double beta decay. We would like to note however that a better limit can be achieved by considering the possibility that the peak at 2528 keV be due to double beta decay to the excited 536 keV level with the absorption of the corresponding de-excitation γ-ray in the same crystal. By evaluating the detection efficiency for this process we achieve a lower limit of 1.6×10^{22} years for neutrinoless double beta decay of ^{130}Te to the 2^+ excited state of ^{130}Xe. This process cannot therefore account for more than 5 and 15% of the geochemically obtained rates in the two extreme results reported before. We have then investigated for the neutrinoless case the above mentioned possibility [15] of a large contribution due to double beta decay to a possible 0^+ state between 1100 and 1200 keV. The best limit is obtained by considering the possibility that the peak at 2528 keV be due to neutrinoless double beta decay to this 0^+ state when *both* the de-excitation gamma ray to the 536 keV state *and* the 536 keV gamma ray are absorbed in the crystal together with the two electrons. By calculating the corresponding efficiency we can set at 90% c.l. an upper limit of 5×10^{21} years for neutrinoless double beta decay to a possible 0^+ state between 1100 and 1200 keV. This contribution does not exceed therefore 15 and 54% of the geochemically obtained rates in the two extreme results reported before.

5. Conclusions

The good performance of our array of twenty cryogenic detectors of TeO_2 in a test run corresponding to slightly more than a week of effective running time allows to set at 90% c.l. a lower limit of 5.6×10^{22} years for the lifetime of neutrinoless double beta decay of ^{130}Te. The corresponding limits on the average antineutrino mass depend considerably on theory [7] and range from 2.9 to 6.1 eV. If these predictions are accepted out limit, together with the geochemical one for ^{128}Te [10–13] is among the more restrictive ones for the various double beta decay candidates [2,6].

Our experiment also shows that the neutrinoless channels do not account for relevant contributions to the double beta decay rates of ^{130}Te obtained in geochemical experiments.

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References

[1] M. Moe, P. Vogel, Ann. Rev. Nucl. Part. Sci. 44 (1994) 247.
[2] V.I. Tretyak, Yu.G. Zdesenko, Atomic data and nuclear data tables 61 (1995) 43.
[3] J. Suhonen, O. Civitarese, Weak-interactions and nuclear-structure aspects of nuclear beta decay, to be published in Physics Reports.
[4] S. Jullian, Review of experimental results on double beta

decay, invited paper to MEDEX97, to be published on Czech Journal of Physics.
[5] A. Balysh et al., Phys. Rev. Lett. 77 (1996) 5186.
[6] L. Baudis et al., Phys. Lett. B 407 (1997).
[7] C.E. Aalseth et al., Nucl. Phys. B (Proc. Suppl.) 48 (1996) 223; F.T. Avignone, The International Germanium Experiment (IGEX) in 1997, invited Talk to TAUP 97, Laboratori Nazionali del Gran Sasso (Italy), September 7–11, 1997, S. Bottino, A. Morales (Eds.), to be Published in Nucl. Phys. (Proc. Suppl.); F. Avignone, private communication.
[8] A. Faessler, Nucl. Phys. A 570 (1994) 39.
[9] H.V. Klapdor-Kleingrothaus, Double beta decay as a sensitive probe of new physics. Theory and experiments, invited paper to NANP-97, International Workshop on non accelerator physics, Dubna, July 6–11, 1997, V. Kovalenko (Ed.).
[10] O.K. Manuel, in: Proc. of the Int. Symp. on Nuclear Beta Decay and Neutrino, Osaka, Japan, World Scientific, Singapore, 1986, p. 71; O.K. Manuel, J. Phys. G, Nucl. Part. Phys. 17 (1991) S221; J.T. Lee, O.K. Manuel, R.I. Thorpe, Nucl. Phys. A 529 (1991) 29; private communication by O.K. Manuel.
[11] T. Kirsten, in: Proc. of the Int. Symp. on Nuclear Beta Decay and Neutrino, Osaka, Japan, World Scientific, Singapore, 1986, p. 81; private communication.
[12] T. Bernatowicz et al., Phys. Rev. Lett. 69 (1992) 2341; Phys. Rev. C 47 (1993) 806.
[13] N. Takaoka, Y. Motomamura, K. Nagao, Phys. Rev. C 53 (1996) 1557.
[14] M.T.F. da Cruz et al., Thick-target yield of iodine isotopes from proton interactions in Te, and the double beta decay of ^{128,130}Te, LBL-33904, Preprint March 29, 1993.
[15] M. Aunola, J. Suhonen, Nucl. Phys. A 602 (1996) 133.
[16] G.F. Dell'Antonio, E. Fiorini, Suppl. Nuovo Cim. 17 (1960) 132.
[17] E. Fiorini, T. Niinikoski, Nucl. Instrum. and Meth. in Phys. Res. 224 (1984) 83.
[18] For recent reviews on cryogenic detectors see D. Twerenbold. Rep. Prog. Phys. 59 (1996) 349; N. Booth, B. Cabrera, E. Fiorini, Ann. Rev. of Nucl. Sci. 46 (1996) 471.
[19] G.R. Dyck et al., Phys. Lett. B 245 (1990) 343.
[20] R.B. Firestone, Table of Isotopes, V.S. Shirley (Ed.), John Wiley and Sons, 1996.
[21] A. Alessandrello et al., Phys. Lett. B 335 (1994) 519.
[22] A. Alessandrello et al., Nucl. Phys. B (Proc. Suppl.) 48 (1996) 238.
[23] A. Alessandrello et al., Phys. Lett. B 384 (1996) 316.
[24] A. Alessandrello et al., Phys. Rev. Lett. 77 (1996) 3319.
[25] A. Alessandrello et al., Phys. Lett. B 408 (1997) 465.
[26] L. Zanotti, J. Phys. G. 17 (1991) S373.
[27] A. Alessandrello et al., Methods for response stabilization in bolometers for rare decays, Nucl. Instrum. and Meth. A, in the press.
[28] A. Alessandrello et al., Measurements of internal radioactive contamination in samples of Roman lead to be used in experiments on rare events, submitted to Nucl. Instrum. and Meth. B.
[29] A. Alessandrello et al., Nucl. Instrum. and Meth. A 370 (1996) 220.