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Preliminary results on the performance of a TeO_2 thermal detector in a search for direct interactions of WIMPs

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Abstract

During a Double Beta Decay experiment performed at Laboratori Nazionali del Gran Sasso, a 1548 hours background spectrum was collected with a 340 g TeO_2 thermal detector. An analysis of this spectrum has been carried out to search for possible WIMP signals. The values for parameters which are essential in the search for WIMPs, like energy resolution (2 keV), energy threshold (13 keV) and nuclear recoil quenching factor (≥ 0.93) have been experimentally determined and are discussed in detail. The spectrum of recoils induced by α decays has been directly observed for the first time in coincidence with the α particle pulse. Preliminary limits on the spin-independent cross sections of WIMPs on Te and O nuclei have been obtained.

1. Introduction

Nowadays the idea that the Universe is dominated by nonluminous matter is well accepted by the scientific community and is proved by a set of several incontrovertible data [1-3]. Evidence for baryonic dark matter has been obtained recently [4,5]. The hot big bang model provides however an important constraint for the baryonic mass density in the Universe: primordial nucleosynthesis predictions are consistent with the measured abundance of light elements only if baryonic dark matter accounts for about 5% of the critical density [6].

Nonbaryonic dark matter could be made by "hot" relics of the big bang like light neutrinos, "cold" relics like Weakly Interacting Particles (WIMPs) and nonthermal relics like axions [2,3]. Light neutrinos (the only candidate particles that are known to exist) could account for the critical density only if at least one of the three neutrino flavours has a mass of about 30 eV, a value which is well behind the experimental limits for ν_μ and ν_τ masses. A predominance of hot dark matter is however inconsistent with cosmological models describing structure formation in the Universe. Furthermore comparison of these models with recent experimental data suggests a dark matter composition of roughly 30% "hot" and 70% "cold" [3,7,8].

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2. WIMPs detection

The existence of WIMPs is foreseen by several theories, the most famous candidates being the heavy neutrino and the Lightest Supersymmetric Particle that – according to the Minimal Supersymmetric Standard Model (MSSM) – is the neutralino [9,10]. If the galactic halo were made of WIMPs, these should have a density of about 0.2–0.5 GeV cm^{-3} [5,11], their velocity distribution in the galactic rest frame being a maxwellian velocity distribution with a cut-off at the galactic escape velocity ($\beta_{\mathrm{esc}} = 2.67\ 10^{-3}$) and with an average velocity $\beta_{\mathrm{rms}} = 1\ 10^{-3}$. WIMPs are supposed to interact with ordinary matter mainly via elastic scattering on nuclei, with a cross section which is dependent both on the nature of the particle and on the nucleus used as a target.

In the case of particles with vector coupling (like the heavy neutrino), which is relevant to this experiment, the spin-independent cross section ($\sigma_{\mathrm{s.i.}}$) for a $\mathrm{Z_0}$ mediated interaction is [3]:

$$\sigma_{\mathrm{s.i.}} = \frac{\mathrm{G_F^2}}{8\pi}\mu_{\mathrm{A}}^2[\mathrm{N} - \mathrm{Z}(1 - 4\sin^2\theta_{\mathrm{W}})]^2, \qquad (1)$$

where μ_{A} is the WIMP-nucleus reduced mass, Z and N are the proton and neutron numbers of the target nucleus, $\mathrm{G_F}$ is the Fermi coupling constant and θ_{W} is the Weinberg angle. These cross sections are referred to point-like interactions. When the wavelength associated with the momentum transfer from WIMPs to nuclei is comparable with the nuclear radius, the interaction is no longer point-like and form factors have to be introduced to account for this effect [3,10]. The most realistic form factor seems at present to be the one reported by Engel [12] which we adopt here.

Direct detection of WIMPs is based on the measurement of the continuous spectrum of nuclear recoils produced in the interaction of these particles with the nuclei of a suitable detector. This technique has a strong limitation: the background due to spurious events produces a continuum with a similar shape as the spectrum of nuclear recoils. The signal due to WIMP could be identified by observation of the seasonal effect, but this requires large masses and long running times. Lacking evidence of a dark matter contribution to the measured background spectra only an exclusion plot for the WIMP-nucleus cross sections versus WIMP mass can be obtained.

Semiconductor [13], scintillation [14] and thermal detectors [15–17] have been proposed or have already been used in dark matter experiments and the debate on which of the different devices should be better suited to search for WIMPs is still open [2,3,17]. Various parameters contribute to determine the experimental sensitivity:

(i) *number of target nuclei* (the mass of the detector) and *counting time* of the experiment. These parameters play however practically no role in the experiments performed so far yielding exclusion plots only, since in this case only the observed rate per unit mass and time is important;

(ii) *background counting rate.* Radioactivity and cosmic rays are the most important sources of spurious events. To reduce their contribution, WIMP searching experiments must be performed with heavily shielded detectors in underground laboratories;

(iii) *energy threshold.* The maximum sensitivity for WIMP-nucleus interactions is obtained for low recoiling energies thus the energy threshold of the detector must be kept as low as possible;

(iv) nuclear recoil *quenching factor*, i.e. sensitivity of the employed device to nuclear recoils;

(v) total detection *efficiency*, which must take into account any kind of signal loss that could be produced during both data acquisition and data analysis.

Although not included in this list, the energy resolution of the detector plays an important role in determining the value of the experimental sensitivity. This is in fact strictly connected to the energy threshold achievable with the device and provides a precious help for background identification and rejection.

Of the above reported parameters, one which is dramatically dependent on the kind of detector used is the nuclear recoil quenching factor Q. This parameter is expressed as the ratio between the amplitude of a nuclear recoil signal to the amplitude of a signal produced by an electron of the same energy. Detectors are normally calibrated with electrons or – more generally and yielding the same results – with γ or X photons. Their response to a slower, less ionizing particle (as a nuclear recoil) is generally different. The quenching factor is the conversion parameter which allows to attribute to each particle its true value of energy. Energy resolution, energy threshold and counting rates quoted for detectors are always evaluated on the basis of an electron calibration. When referred to detection of nuclear recoils induced by WIMPs these parameters have to be converted – by means of the quenching factor – to the corresponding values for nuclear recoils. Theoretical estimates of the quenching factor are provided by the theory of Lindhard et al. [18], but experimental measurements have to be performed to verify the validity of this theory at the energies and for the nuclei of interest for dark matter search.

Semiconductor and scintillation devices are generally characterised by low values of the quenching factor. In neutron scattering experiments, quenching factors ranging between 0.25 and 0.40 have been measured in Si detectors (for recoil energies between 3 and 20 keV) [19] and in Ge detectors (for recoil energies between 20 and 100 keV) [20]. The quenching factors of NaI and CaF_2 scintillators have been measured in neutron scattering experiments, yielding values between 0.05 (Ca for recoil energies of 100 keV) and 0.25 (Na for recoil energies of about 10 keV) [21]. Considerably better seems to be the situation for liquid Xe scintillators: a value of 0.8 has been evaluated for the Xe quenching factor using the predictions of Lindhard et al. and taking into account the effects of recombination [22].

Quite different is the situation for thermal detectors [16,17] which we discuss here in some detail. As reported later and in a further publication [23], our group has measured with TeO_2 thermal detectors a quenching factor of ~ 0.93 for nuclear recoils (^{206}Pb) of 100 keV [23,24]. A similar value for the same recoil has been obtained by the EDELWEISS Collaboration [25] for the quenching factor of a diamond bolometer. Thermal detectors should have in principle a unit quenching factor, since they are not sensitive to the ionisation energy only, but to the whole energy released by the particle into the absorber and converted into heat. The observed difference from unity can be interpreted as follows.

A fraction α of the energy lost by the particle in the absorber is released to the nuclear system (displacing ions from their lattice sites) and only a fraction ε of it is definitely converted into heat. The remaining fraction $(1-\alpha)$ of the lost energy is released to the electronic system, and again only a fraction δ of it is definitely converted into heat. While α depends both on projectile and target, ε and δ depend essentially only on the absorber, if secondary effects, like, e.g. different specific ionization, are neglected. In the case of an electron the energy is usually totally released to the electronic system ($\alpha = 0$), while for other particles (e.g. a low energy heavy ion) part of it is released also to the nuclear system.

The quenching factor can generally be parametrized as $Q = \frac{1}{\delta}[\delta(1-\alpha)+\varepsilon\alpha]$. In the limiting case that the whole energy is transferred to the nuclear system the quenching factor is $Q_N = \varepsilon/\delta$. It should be noted that, depending on the absorber, Q_N can assume values both greater and lower than unity. Theoretical considerations, supported by several experimental measurements [26,27], allow to evaluate the value of α for any projectile/target system. It increases with decreasing values of E, approaching however a constant common value α_{th} for $E < E_{th}$. The energy threshold E_{th} depends on the nature of both projectile (recoiling nucleus) and target: in the case of a TeO_2 crystal E_{th} is of about 500 keV, 2 MeV and 10 keV for Te, Pb and O recoils, respectively. Below these values the quenching factor $Q_{th} = \frac{1}{\delta}[\delta(1-\alpha_{th})+\varepsilon\alpha_{th}]$ is constant. When $\varepsilon < \delta$, as in our case, Q_{th} is the *lowest* possible value for the quenching factor and is *independent* on the projectile (recoiling nucleus) as long as its energy is *below* E_{th}. The above mentioned quenching factor of 0.93 has been obtained for TeO_2 bolometers in such conditions, namely for ^{206}Pb recoils below threshold. As a consequence this value has to be assumed as the quenching factor for *any* projectile as long as its energy is *below threshold* (e.g. with $E < 500$ keV for Te, $E < 10$ keV for O, etc.). The quenching factor for particles with energy *above threshold* can be considerably larger and varies with the type of particle. Our group has in fact verified [23,24] that for α particles of a few MeV and therefore largely above E_{th}, the quenching factor is > 0.99.

As a last point it is worth to discuss the problem related to the fourth parameter contributing to the sensitivity: the total detection efficiency. A quantitative evaluation of this parameter is of primary importance and implies a measurement (in the energy region of interest) of the detector efficiency and of the probability of having signal losses during data acquisition or during data analysis. Therefore, when signal rejection techniques (like those based on the distinction between low and high ionizing events) or background subtraction procedures (involving identification and localisation of the radioactive contaminants surrounding the detector) are applied, a quantitative analysis of the reliability of the used algorithms has to be carried out.

3. Experimental details

Our group has performed a series of experiments searching for Double Beta Decay (DBD) of ^{130}Te with TeO$_2$ bolometers [24,28]. As in the case of dark matter searches, DBD experiments require long time measurements of the background spectrum and the background reduction plays a fundamental role if high sensitivities have to be reached.

The result reported here is a by-product of a measurement carried out with an array of four TeO$_2$ bolometers operated by our group in the underground facility of the Laboratori Nazionali del Gran Sasso (Italy) [28]. A dark matter analysis was carried out considering only the background spectrum (1548.4 h) collected with one of the four 340 g bolometers of the array. This choice is due simply to the better performance of this detector with respect to the others of the array, implying a better energy resolution and a lower energy threshold.

The calibration of the spectrum is obtained using all identified X and γ-lines due to internal and external contaminations of the detector (mainly in uranium and thorium). The spectrum in the low energy region (Fig. 1) shows several identified lines. The lines at 27 and 31 keV are due to Te X-rays and to K-capture of ^{123}Te (0.905% natural abundance), respectively. Our measured rate for the latter seems much lower than reported in the literature and is presently being studied. At higher energy one can easily identify the 46.5 keV γ-line of ^{210}Pb and the X-ray lines due to lead. The peaks at 92.6 and 88.3 keV are due to $^{234\mathrm{m}}$Th and to $^{127\mathrm{m}}$Te produced by activation of ^{126}Te by cosmic ray neutrons. All these lines allow a careful control of the linearity of our detector and yield a FWHM resolution of about 2 keV in the low energy region. The uniformity in response over the whole detector volume is proved by the agreement between the energy resolution obtained with gamma calibrations and the energy resolution which could be predicted on the basis of noise measurements. Moreover a systematic analysis of the counting rate near threshold has demonstrated its stability in time.

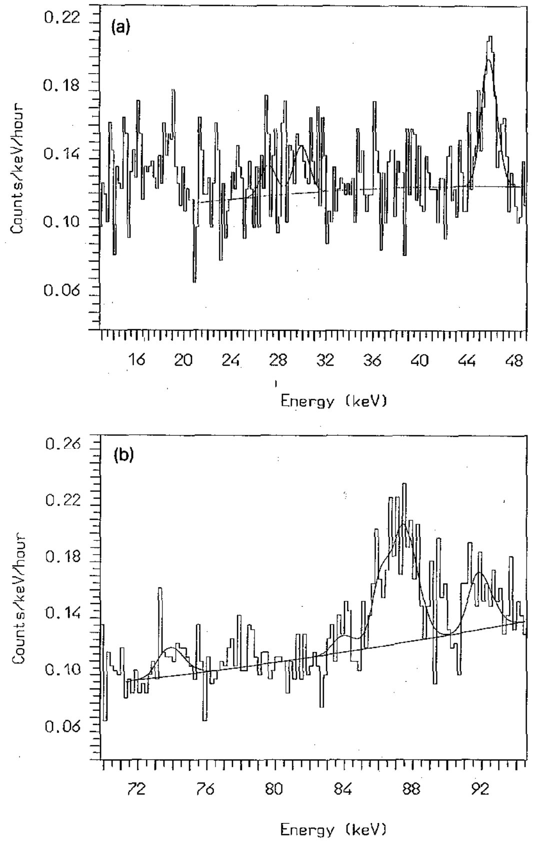

Fig. 1. The spectrum in the low energy region.

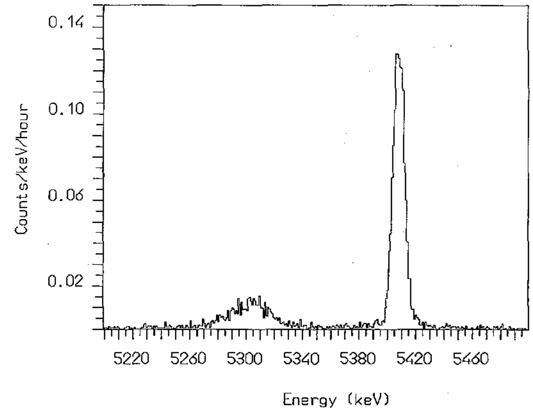

Fig. 2. The "doublet" of the 5407 α-peak.

Two peaks appearing in the high energy region and attributed to α decay of ^{210}Po internal and external contaminations of the TeO$_2$ crystal, are used to evaluate the quenching factor of our device (Fig. 2). ^{210}Po decays with a transition energy of 5407 keV emitting an α particle of 5304 keV. The peak appearing on the high energy side of the spectrum is due to an internal contamination of ^{210}Po (its counting rate decreases in time with a decay constant that is in good agreement with the lifetime of this isotope). Since both the α particle and the recoiling nucleus contribute to the signal, this line corresponds to the 5407 keV transition energy. The peak on the low energy side is due to an external contamination in the same isotope; in this case the signal is produced by the α particle only and its energy is 5304 keV. The separation between the two peaks, obtained by calibrating the spectrum in the high energy region using all identified alpha lines, is 95.5 ± 1 keV to be compared with the expected value of 103 keV. In this same experiment we were able also to measure directly the energy release due to ^{206}Pb recoils. Fig. 3 shows the spectrum obtained in our bolometer by selecting only events in coincidence with a signal of a 5304 keV α particle in the nearby crystals (the other three elements of the array). The asymmetry of the peak due to ^{206}Pb recoils is obviously due to energy loss of these nuclei in the surface of the emitting crystal. The recoiling energy is found to be 96 ± 3 keV in excellent agreement with the value obtained from the peak separation. The quenching factor is thus evaluated to be 0.93 ± 0.03. As discussed before this value has to be considered as the *lower limit* for the quenching factor of *any* projectile in our detector. We note that a similar value (0.98 ± 0.03) has been obtained [25] by directly exposing to a very thin ^{210}Po source a diamond wafer acting as absorber with a chemically doped Ge thermistor in thermal contact with it.

For our search for WIMPs we have evaluated an energy threshold of 13 keV, and a total detection efficiency of (97 ± 2)%, taking into account any probability of signal loss during data acquisition or data analysis.

4. Data analysis

Lacking any signature of our events as a result of WIMP interactions, we have conservatively assumed that all background counts were due to WIMP-nucleus elastic scattering processes obtaining therefore only limits on the strength of the vector WIMP-nucleus coupling. In this analysis a value of 0.3 GeV cm^{-3} has been assumed for ρ_{halo} and Te and O contributions have been considered separately leading to worst, *but model independent*, limits (Fig. 4).

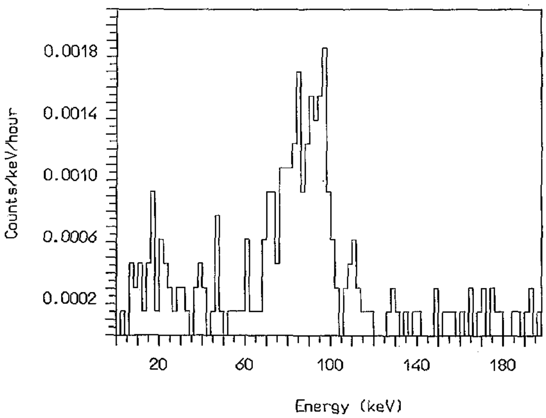

Fig. 3. The spectrum of nuclear recoils from ^{210}Po surface contamination.

Table 1
Peaks at low energy.

Meas. energy (keV)	Rate (c/h)	Interpretation	Expected energy (keV)
27.3 ± 0.3	0.07 ± 0.02	Te X-rays	27.4
30.4 ± 0.3	0.056 ± 0.023	Te K-capture	30.5
46.2 ± 0.2	0.21 ± 0.04	^{210}Pb	46.6
73.5 ± 0.2	0.044 ± 0.015	Pb X-rays	72.8
75.2 ± 0.3	0.036 ± 0.015	Pb X-rays	74.9
84.6 ± 0.6	(0.020 ± 0.015)	Pb X-rays	84.7
86.8 ± 0.1	0.102 ± 0.023	Pb X-rays	87.3
88.1 ± 0.1	0.075 ± 0.021	^{127m}Te 88.3	
92.3 ± 0.2	0.061 ± 0.019	^{234m}Th	92.6

No previous measurements on Te and O nuclei to which our results can be compared have been reported so far. If our cross sections are scaled, necessarily in a model dependent way, to other nuclei or to single nucleons our limits are admittedly less stringent than those obtained on Ge and Na and on Si for large and low WIMP mass, respectively. The same is true for the limits on the mass for a hypothetical heavy neutrino which is excluded for masses between 20 and 200 GeV. We would like however to note that our experiment is the only one where the quenching factor for the nuclear recoil is directly measured in the dark matter detector itself and that the energy is calibrated down to the region of interest.

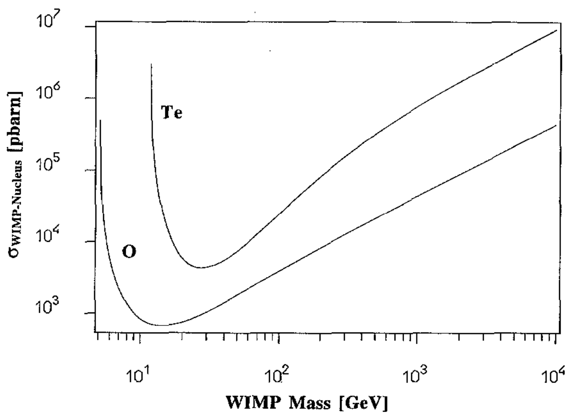

Fig. 4. Exclusion plot for cross sections on nuclei for Te and O.

5. Conclusions

The present result shows the potentiality of thermal devices in the detection of WIMPs. We recall here that it has been obtained as a by-product of a Double Beta Decay experiment with a detector which was optimised to work at much higher energies than those of interest for dark matter searches (i.e. in the MeV range where the neutrinoless Double Beta Decay signal of ^{130}Te should appear). Lower values of the energy threshold and of the background counting rate could be obtained by improving the detector performances at low energy and by reducing the radioactive background in the same region. This background is presently dominated by bremsstrahlung due to ^{210}Pb contamination of the lead shield surrounding the cryostat, which does not affect the high energy neutrinoless DBD region.

Our group is constructing an array of 20 TeO_2 bolometers of 340 g each for a new DBD experiment. The array will be completely surrounded by a 4 cm thick shield made with ancient roman lead, whose ^{210}Pb contamination is practically zero, thus eliminating this source of background. A larger array of more than one hundred such bolometers is planned and will allow a very sensitive search on the seasonal variation of the signal due to direct interactions of WIMPs. 1

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