Cosmogenic activation of a natural tellurium target

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Abstract

^{130}Te is one of the candidates for the search for neutrinoless double beta decay. It is currently planned to be used by two experiments: CUORE and SNO+. In the CUORE experiment TeO_2 crystals cooled at cryogenic temperatures will be used. In the SNO+ experiment ^{nat}Te will be deployed up to 0.3% loading in the liquid scintillator volume. A possible background for the signal searched for, are the high Q-value, long lived isotopes, produced by cosmogenic neutron and proton spallation reaction on the target material. A total of 21 isotopes with Q-value larger than 2 MeV and $T_{1/2}$ >20 days have been identified as potential backgrounds. In addition low Q-value, high rate isotopes can be problematic due to pile-up effects, specially in liquid scintillator based detectors. Production rates have been calculated using the ACTIVIA program, the TENDL database, and the cosmogenic neutron and proton flux parametrization at sea level from Armstrong and Gehrles for both long and short lived isotopes. The obtained values for the cross sections are compared with the existing experimental data and calculations. Good agreement has been generally found. The results have been applied to the SNO+ experiment for one year of exposure at sea level. Two possible cases have been considered: a two years of cooling down period deep underground, or a first purification on surface and 6 months of cooling down deep underground. Deep underground activation at the SNOLAB location has been considered.

Keywords: cosmogenic activation, double beta decay, cosmic flux, cross section

1. Introduction

The neutrino was introduced for the first time by Pauli in 1930 as a solution for the beta-decay spectrum. Initially considered as a massless particle, during the period from 1990 to 2006 the SNO [1] and the SuperK [2] oscillation experiments proved that neutrinos change their flavour when travelling from the source to the detector. This property was already known in the quark sector and happens only if the particles involved do have mass. The existence of massive neutrinos has been introduced within extensions of the Standard Model. Two types of neutrino masses are allowed, the Dirac and the Majorana ones. In the Majorana case neutrinos and their anti-particles are the same.

The investigation of the neutrino's nature is one of the most active fields in modern neutrino physics. The search of the Majorana nature of neutrinos is done in the Double-Beta-Decay (DBD) experiments [3]. The DBD is a nuclear process where the Z number changes by 2 units while the atomic mass, A, does not change. It happens only if the single beta decay transition is strongly forbidden or suppressed. If neutrinos are Majorana particles, the decay can proceed without the emission of the 2 neutrinos. The result is the presence of a peak at the Q-value of the reaction in the sum spectrum of the two electrons.

There are about 35 candidate nuclei for the DBD searches. The quantity extracted from the number of events in the peak is the half-life of the decay. The expected value for the half life is larger than 10^{26} years. To search for such a rare event a large mass (volume), a very low background environment and a good knowledge of the backgrounds in the detector are necessary.

A possible source of background is the activation of the candidate material through spallation reaction induced by cosmogenic neutrons and protons during handling on surface. A study of the cosmogenic induced isotopes has been done for several double beta decay experiments, like GERDA [4] and CUORE [5], in order to define the maximum allowed exposure on surface, the necessary shielding during transportation, the necessary purification factors, and the cooling down time underground (UG) to reduce the cosmogenic background to a negligible level.

In this article the studies are focussed on the calculation of the production rates for several isotopes produced by neutrons and protons interaction in a natural tellurium target. ^{130}Te is the candidate nucleus chosen by the CUORE and the SNO+ collaborations for the search for the neutrinoless double beta decay. ^{130}Te has a high natural isotopic abundance of 34.08% and a relative high Q-value of 2.53 MeV. The CUORE collaboration will use tellurium in form of crystals (TeO_2) cooled at cryogenic temperatures. The energy resolution of the crystals is nearly 5–7 keV (FWHM) at 2.53 MeV [6]. The cosmogenic induced isotopes identified as possible background by the collaboration are ^{60}Co, ^{124}Sb and ^{110}Ag^{m}. The calculated exposure time at sea level for the Te crystals in [5] was 4 months, followed by 2 years of storage underground.

Liquid scintillator based detectors, like the SNO+ experiment, however, are expected to have a much worse energy resolution

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than bolometers. In addition, the total energy (beta plus gammas) released in a decay is measured. As a consequence the number of possible cosmogenic induced backgrounds that has to be taken into account is larger.

2. Isotopes

The isotopes identified as possible direct backgrounds for the double beta decay search in Te-based experiment are summarized in table 1. The $T_{1/2}$, Q-value and the decay mode are shown. The decay branching ratio (BR) is listed in brackets when different from 100%. Isotopes are selected according to the following:

- $T_{1/2}$ > 20 days. Shorter lived isotopes are generally considered to be removed by a cooling down time of few months. A cooling down time of about 6 months will reduce the initial activity of at least a factor 560 for a 20 days lived isotope. Shorter lived isotopes are considered when fed by a long lived parent.
- Q-value larger than 2 MeV.
- Mass number, A, smaller than ^{131}I, since the isotopes are supposed to be produced by spallation reactions on Te. Isotopes with higher mass number can be produced only if contaminations are present in the target material.

In some cases, isotopes are both directly produced in the reaction, and fed by the decay of a long lived parent also produced in the target material. If the half-life of the daughter is much shorter than the parent one, secular equilibrium is assumed. Otherwise, both contributions are taken into account. This is for instance the case for ^{88}Y that can be directly produced in spallation reactions, but also fed by the decay of ^{88}Zr.

2.1. Other possible background isotopes

Long-lived low Q-value isotopes can be a background for the search for neutrinoless double beta decay if their decay rate is high enough to produce pile-up background.
Short-lived, high Q-value isotopes, on the other hand, can have high production rates that will require a long cooling down time underground. A summary of the low Q-value isotopes and the short lived ones is shown in table 2.

3. Cosmogenic flux parametrization at sea level

At sea level the nucleon component of cosmic rays is mainly neutrons (95%), protons (3%) and pions (2%). Protons, despite the small flux, are harder than neutrons. They are stopped more efficiently by shielding around the target.
Different flux parametrizations exist for the neutron and the proton fluxes at sea level. The most common are the one from Ziegler [8], Gordon [9] and Armstrong and Gehrels [10][11]. A comparison for the different flux parametrizations at sea level is shown in fig. 1 in the energy range from 10 MeV to 10 GeV. The parametrizations are referred to NYC. Correction factors due to location and altitude can be quite important: 0.7 for Beijing, 0.81 for Rome, 1.02 for Greater Sudbury (all referred at 0 m altitude) and up to 500 for flight altitudes (39000 feet) [12].
In the following calculation, the parametrization from Armstrong and Gehrels at sea level is used. It is valid for neutrons and protons and it is used in the energy range from 10 MeV to 100 GeV.
The effect of using a different flux parametrization can be quite important, especially for those isotopes that have a higher production rate at E<100 MeV or at E>3 GeV. To the first category belongs ^{124}Sb and most of the isotopes close in atomic number to tellurium. To the second group belong ^{60}Co and ^{110}Ag^m.
Changes in per cent on the expected number of events in one year due to the flux parametrization used are shown in table 3. One year of surface exposure has been assumed in all cases. Differences up to a factor 3 are obtained when a different flux parametrization is used. This effect was also seen in [13].

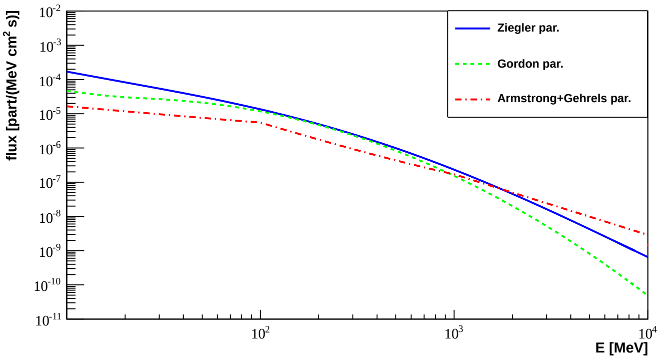

Figure 1: Comparison among the different flux parametrizations at sea level: neutron flux parametrization from Gordon [9] (green, dashed), neutron and proton flux from Armstrong and Gehrels [10][11](red, dashed dotted) and the neutron flux from Ziegler [8] (blue, solid). The Armstrong flux parametrization above 1 GeV is harder than the Ziegler and Gordon neutron ones.

4. Cross sections

The cross sections used for this evaluation are based on the semi-empirical formulas of Tsao and Silberberg [14][15][16]. The formulas are obtained for protons and valid for E>100 MeV. Even if obtained for protons, it is commonly considered that the neutron and proton cross sections are very similar at high energies. The formulas do not discriminate between ground and metastable state.
Due to the lack of data for E>100 MeV only few isotopes cross sections, and only for few energies, can be compared to measurements. Semi-empirical cross section formulas have been integrated in several codes. An extensive comparison of available cross section data and simulation codes has been done by the IDEA collaboration (part of the ILIAS project) in order to find a set of standards for the germanium and tellurium target materials [13]. The code used in the IDEA's evaluation is the YIELDX routine [16] for energy larger than 100 MeV and the MENDL database [17] for the medium-low energy range.

Isotope	$T_{1/2}$ [7] [d]	Q-value [7] [MeV]	Decay mode (BR) (%)
^{22}Na	950.6	2.84	EC, β^+
^{26}Al	2.62E+8	4.00	β^+
^{42}K (direct and daughter of ^{42}Ar)	0.51 (1.20E+4)	3.53	β^-
^{44}Sc (direct and daughter of ^{44}Ti)	0.17 (2.16E+4)	3.65	EC, β^+
^{46}Sc	83.79	2.37	β^-
^{56}Co	77.2	4.57	EC, β^+
^{58}Co	70.9	2.31	EC, β^+
^{60}Co (direct and daughter of ^{60}Fe)	1925.27 (5.48E+8)	2.82	β^-
^{68}Ga (direct and daughter of ^{68}Ge)	4.70E-2(271)	2.92	EC, β^+
^{82}Rb (daughter of ^{82}Sr)	8.75E-3(25.35)	4.40	EC, β^+
^{84}Rb	32.8	2.69	EC, β^+ (96.1)
^{88}Y (direct and daughter of ^{88}Zr)	106.63 (83.4)	3.62	EC, β^+
^{90}Y (direct and daughter of ^{90}Sr)	2.67 (1.05E+4)	2.28	β^-
^{102}Rh (direct and daughter of ^{102m}Rh) [a]	207.3	2.32	EC, β^+ (78)
^{102m}Rh	1366.77	2.46	EC (99.77)
^{106}Rh (daughter of ^{106}Ru)	3.47E-4 (371.8)	3.54	β^-
^{110m}Ag	249.83	3.01	β^- (98.67)
^{110}Ag (daughter of ^{110m}Ag)[b]	2.85E-4	2.89	β^-(99.70)
^{124}Sb	60.2	2.90	β^-
^{126m}Sb (direct and daughter of ^{126}Sn)	0.01 (8.40E7)	3.69	β^- (86)
^{126}Sb (direct and daughter of ^{126m}Sb)[c]	12.35 (0.01)	3.67	β^-

[a] 0.23% from ^{102m}Rh IT decay.
[b] 1.33% from ^{110m}Ag IT decay
[c] 14% from ^{126m}Sb IT decay.

Table 1: Possible background isotopes induced by cosmogenic neutrons and protons on a natural Te target. The isotopes selection criteria are described in the text. $T_{1/2}$, Q-value and decay modes are shown. When the branching ratio (BR) is different from 100%, the value is specified in brackets.

In this analysis the ACTIVIA code [18] and the YIELDX routine are used. Both codes use the most up-to-date cross section formulas from 1998. The ACTIVIA code provides directly the isotope production rates for a natural target and a range of energies, while the YIELDX routine provides only cross section values for a certain energy and a particular isotope. In addition, the ACTIVIA code includes the feeding from short lived parents. A comparison of the production rates for the isotopes listed in table 1 using different codes has been done. A ^{nat}Te target has been assumed. The results are shown in column 2 of table 3.
In the low energy range neutron and proton cross sections can be very different. For this reason, when available, the TENDL database [19] has been used from 10 MeV to 200 MeV. TENDL-2009 has been used in the following calculations. A comparison with the more up-to-date TENDL-2012 database has been done and included in column 2 of table 3.

4.1. ^{60}Co

^{60}Co is one of the most dangerous backgrounds for the search for neutrinoless double beta decay of ^{130}Te both in bolometers and liquid scintillator based experiments. In the decay (Q-value of 2.82 MeV) two gammas (sum energy of 2.5 MeV) and one beta are emitted. In figure 2 a comparison between the ACTIVIA and the YIELDX codes is shown together with the measured cross section data from [20][21]. The ACTIVIA code shows a better agreement with the experimental data.

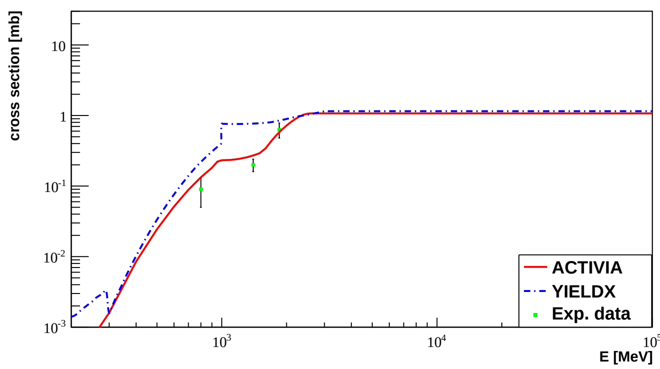

Figure 2: Comparison for the ^{60}Co excitation function obtained with the ACTIVIA code (red, solid) and the YIELDX routine (blue, dashed dotted). Experimental data are from [20][21]. The ACTIVIA code agrees better to the experimental data.

4.2. $^{110}Ag^m$

In figure 3 the comparison for the ^{110}Ag^m excitation function is shown. Above 800 MeV, the cross section was measured for two energies (1.4 GeV and 23 GeV) [20]. The agreement with the ACTIVIA code is fairly good (deviation factor of 1.3 for 1.4 GeV and 1.06 for 23 GeV energies [13]). The experimental data point at 800 MeV [20] shows a larger deviation.

Isotope	$T_{1/2}$ [7] [d]	Q-value [7] [MeV]	Decay mode (BR) (%)
^{118}Sb (fed by ^{118}Te)	0.0025	3.66	β^+, EC
^{120m}Sb	5.76	2.68	EC
^{125}Sb	1008	0.77	β^-
^{127}Sb	3.85	1.58	β^-
^{129}Sb	0.18	2.38	β^-
^{125}Sn	9.64	2.36	β^-
^{126}I	12.98	2.16 (EC)/1.26 (β^-)	EC (52.7), β^- (47.3)
^{118}Te (feed ^{118}Sb)	6	0.28	EC
^{121}Te	19.17	1.05	EC
^{121m}Te	164.2	1.35 (EC), 0.29 (IT)	EC, β^+ (11.4), IT (88.6)
^{127m}Te (fed by ^{127}Sb)	106.1	0.79 (β^-), 0.09 (IT)	β^- (2.4%), IT (97.6)
^{129m}Te	33.6	1.60 (β^-), 0.11 (IT)	β^-(37), IT(63)
^{121m}Sn	16034	0.40 (β^-), 0.006 (IT)	β^-(22.4), IT(77.6)
^{123}Sn	129.2	1.40	β^-
^{129}I	5.73e9	0.19	β^-
^{125}I	59.4	0.19	EC

Table 2: Short lived isotopes and low Q-value isotopes that can be produced by cosmogenic activation of a natural Te sample.

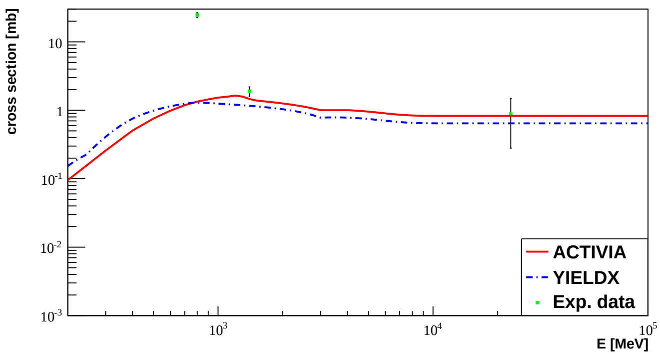

Figure 3: Comparison for the ^{110}Ag^m excitation function obtained with the ACTIVIA code (red, solid) and the YIELDX routine (blue, dashed dotted). Experimental data are from [20]. The ACTIVIA code is more close to experimental data for E>800 MeV.

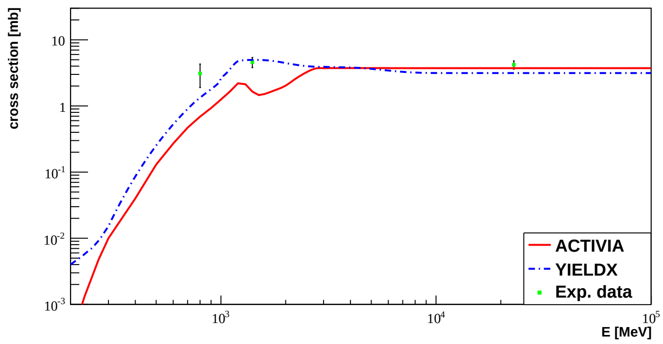

Figure 4: Comparison for the ^{88}Y excitation function obtained with the ACTIVIA code (red, solid) and the YIELDX routine (blue, dashed dotted). Experimental data are from [20]. The values from the ACTIVIA code show a better agreement with the experimental data for high energies.

A recent measurement at the LANSCE facility [22] in the energy range from 1.25 MeV to 800 MeV, gives an averaged cross section of 0.18 mb over the entire energy range. The result at 800 MeV shows a better agreement with the semi-empirical formulas than the measurement in [20].

4.3. ^{88}Y

^{88}Y is also one of the possible important backgrounds for the search for the neutrinoless double beta decay of ^{130}Te. The excitation function comparison between the two codes and the experimental data is shown in figure 4. The deviation factors between experimental data and values obtained with the ACTIVIA code are 4.5, 2.8 and 1.1 for the 800 MeV, 1.4 GeV and 23 GeV energies respectively. A good agreement is found for E>1 GeV for the ACTIVIA code.

5. Cosmogenic induced background

The expected production rates are calculated using the ACTIVIA code for the isotopes listed in table 1. Corrections are applied when an isotope is directly produced by cosmogenic spallation reactions and simultaneously formed by the decay of another radionuclide born in the target. This is for instance the case for ^{60}Co, which can be produced by cosmogenic neutron and proton bombardment on a ^{nat}Te target or by the decay of ^{60}Fe. The formulas used to calculate the expected activity are the following [23]:

$$\begin{aligned}
A_1^{EOB} &= R_1(1 - e^{-\lambda_1 t_{exp}}),\\
A_1(t) &= A_1^{EOB} e^{-\lambda_1 t},\\
A_2^{EOB} &= R_2(1 - e^{-\lambda_2 t_{exp}}) +\\
&\quad + R_1\left(1 - \frac{\lambda_2}{\lambda_2 - \lambda_1} e^{-\lambda_1 t_{exp}} + \frac{\lambda_1}{\lambda_2 - \lambda_1} e^{-\lambda_2 t_{exp}}\right),\\
A_2(t) &= A_2^{EOB} e^{-\lambda_2 t} + A_1^{EOB} \cdot \frac{\lambda_2}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t}),
\end{aligned} \tag{1}$$

Isotope	% Change cross section %	% Change flux Ziegler %	% Change flux Gordon %
^{22}Na	28.8	-52.6	-80.9
^{26}Al	26.4	-52.4	-80.7
^{42}K (daughter of ^{42}Ar)	-14.6	-35.2	-70.8
^{44}Sc (daughter of ^{44}Ti)	13.5	-52.8	-80.8
^{46}Sc	-22.3	-47.4	-78.7
^{56}Co	46.8	-51.9	-80.2
^{58}Co	60.2	-36.4	-69.1
^{60}Co (+ ^{60}Fe)	34.4	-34.5	-68.9
^{68}Ga (daughter of ^{68}Ge)	42.2	-35.8	-68.4
^{82}Rb (daughter of ^{82}Sr)	56.5	-31.4	-65.2
^{84}Rb	41.5	-31.4	-66.4
^{88}Y (+ ^{88}Zr)	11.9	-28.5	-63.3
^{90}Y (daughter of ^{90}Sr)	-41.2	-32.6	-68.5
^{102}Rh	17.9	12.4	-27.4
^{102m}Rh	17.9	12.4	-27.4
^{106}Rh (daughter of ^{106}Ru)	32.8	24.1	-15.5
^{110m}Ag	-3.2	47.3	9.4
^{124}Sb	-2.4	184.4	143.0
^{126m}Sb (direct and daughter of ^{126}Sn)	-0.6	250.9	122.1
^{126}Sb (direct and daughter of ^{126m}Sb)	-3.9	167.6	126.4

Table 3: Change in % for the expected activities when a different cross section or flux parametrization is used. The reference is the number of events obtained in one year, for one year exposure at sea level, with the ACTIVIA code [18] for E>200 MeV and the TENDL-2009 [19] for E<200 MeV. See text. Col.2: % difference in the expected number of events when a different routine is used to obtain the cross section values. In the high energy range (E>100 MeV) the YIELDX routine [16] has been used, while in the low energy range (10 MeV< E < 200 MeV) the TENDL-2012 database has been used, when available. Col.3: % difference in the expected number of events when the flux parametrization from Ziegler is used [8]. Col.4: % difference in the expected number of events when the flux parametrization from Gordon is used [9].

where 1 and 2 are the index for the parent and daughter nuclide respectively. A^{EOB} is the activity at the end of bombardment (t_{exp}) and R is the production rate. Results are shown in table 4. The expected number of events has been calculated assuming one year of surface exposure and two different cooling down scenarios:

1. A first purification stage on surface and additional 6 months of cooling down time deep underground. The purification factor (PF) has been assumed to be 10^{-4}. Recent results in [24] show that this factor can be achieved in a two step re-crystallization process. After the purification an additional exposure of 5 hours has been assumed to account for the time needed to transport the material underground;
2. Two years of cooling down deep underground.

Decay branching ratios are taken into account to calculate the number of events expected in one year.
The production rates for ^{60}Co on ^{nat}Te in the energy range from 10 MeV to 100 GeV (10 MeV energy step) has been calculated to be 0.81 μBq/kg. This value is the same obtained in [18].
A cross check with the production rate obtained by the IDEA group for the 10 MeV to 10 GeV energy range using the flux parametrization from Armstrong and the YIELDX routine, shows a very good agreement (predicted value of 0.7 μBq/kg for TeO_2 [13]).

6. Underground activation

In order to reduce the cosmogenic induced background to a negligible level, it is necessary to minimize the exposure time of the material on surface and to maximize the storage underground. In addition, purification techniques could help reducing the produced background isotopes.
Underground, the material can be re-activated by the local neutron flux. However, the underground activation has a smaller impact with respect to the one on surface. In the particular case of the SNO+ experiment, tellurium will be stored at SNOLAB underground lab, at a depth of about 2 km. At this location the major contributions to the neutron flux are:

- Neutrons from (α,n) reaction in the rock. The total flux has been estimated to be around 4000 n/(m^{2}d) [25][27] for norite rock. The neutron energy is below 15 MeV and peaked around 2.5 MeV [28];
- Neutrons induced by muon interactions in the rock. The muon induced neutron flux is summarized in [29] and has an energy up to 3.5 GeV. The integrated flux is $5.4\cdot10^{-11}$ n/(s$\cdot$cm^2). This flux is about a factor 60 smaller than the one at LNGS, where CUORE is located;
- Thermal neutrons from the rock. The total thermal neutron flux is about 4145 n/(m^{2}d) [30]. The isotopes produced by thermal neutron activation on ^{nat}Te are low in Q-value and/or short lived. The presence of a water shielding

Isotope	R (ϕ from [10][11])	Events/t in 1 yr			
	[μBq/kg]	t_{exp}=1 yr	PF = 10^{-4}+5h	t_{cool}=6 months	t_{cool}=2 yrs
^{22}Na	1.01	6.54E+3	4.90	4.29	3.84E+3
^{26}Al	0.67	0.02	1.37E-5	1.37E-5	0.02
^{42}K	1.33 (0.24)	85.11+156.25	20.87+0.11	0.10	149.806
^{44}Sc	1.19 (0.052)	24.54+19.02	14.29+0.01	0.01	18.58
^{46}Sc	1.97	1.86E+4	35.56	7.85	44.21
^{56}Co	0.13	1.12E+3	2.29	0.45	1.60
^{58}Co	1.29	1.08E+4	23.62	3.96	8.51
^{60}Co	0.81 (0.367)	2.95E+3	2.09	1.96	2.27E+3
^{68}Ga	3.14 (1.28)	21.17+1.59E+4	17.55+15.58	9.77	2.46E+3
^{82}Rb	(2.44)	7.71E+3	44.58	0.30	1.63E-5
^{84}Rb	1.29	5.06E+3	22.76	0.50	1.00E-3
^{88}Y	3.14 (8.11)	1.67E+5	176.68	99.05	3.19E+3
^{90}Y	2.69 (0.165)	229.22+122.35	12.10+0.08	0.08	116.63
^{102}Rh	11.77 (0.03)	1.18E+5	128.31	89.37	1.03E+4
^{102m}Rh	11.77	5.72E+4	41.46	37.88	3.95E+4
^{106}Rh	(0.06)	655.58	0.58	0.41	167.948
^{110m}Ag	2.34	2.92E+4	29.38	17.70	3.84E+3
^{110}Ag	(0.03)	393.27	0.40	0.24	51.82
^{124}Sb	182.0	1.33E+6	3.36E+3	409.77	294.741
^{126m}Sb	71.42 (7.91)	102.46	101.81	4.32E-4	0.64
^{126}Sb	89.65 (^{126m}Sb)	1.53E+5	1.80E+3	0.06	0.10

Table 4: Expected production rate (R) estimation for the isotopes listed in table 1. The values are obtained using the ACTIVIA code [18] for E>100 MeV (energy step of 10 MeV). If available the cross sections for E<200 MeV are obtained from the TENDL-2009 database [19] (energy step of 10 eV). The flux parametrization is the one from Armstrong and Gehrels [10][11]. Feeding chains have been included. Parent isotope production rates are given in brackets. For short lived isotopes fed by a long lived parent secular equilibrium has been assumed. No correction factors are applied for the location on surface. Expected numbers of events are given for one year and per tonne (t) of material. The decay branching ratios are taken into account. When short lived isotopes are fed by long lived ones the two contributions are given separately. The two different scenarios are outlined in the text.

around the detector, like in the case of SNO+, reduces the thermal neutron flux.

For the isotopes shown in table 1, the underground activation has been estimated to be less than 1 event/(yr·t) at the SNOLAB depth.
For the isotopes listed in table 2, the production rates both at sea level and underground are shown in table 5. For one year of surface exposure and 6 months of cooling down underground the major contribution comes from ^{127}Te^{m} with a rate of about 0.25 Bq/t.
An important isotope that can be produced by in-situ thermal neutron capture is ^{131}Te^{m} (Q-value=2.41 MeV, $T_{1/2}$=33.25 h). It can only be produced by thermal neutron capture on ^{130}Te. An additional source of in-situ neutrons are the (α,n) reactions on the atoms of the liquid scintillator. The ratio of thermal neutron capture on ^{nat}Te with respect to the one on protons for the case of the SNO+ experiment (0.3% loading), is 0.28%. A small fraction of this (about 1.4%) is on ^{130}Te.

7. Conclusion

In this article the production rate for cosmogenic induced isotopes on a natural tellurium target has been calculated. An extensive set of isotopes with Q-value larger than 2 MeV and $T_{1/2}$ larger than 20 days has been considered as potential background candidates. In addition, the production rates of shorter lived and low Q-value isotopes close in atomic mass to tellurium have been studied. High event rates can produce pile-up background. Production rates are obtained with the help of the ACTIVIA code for E>200 MeV and the neutron and proton cross section database for E<200 MeV when available. The standard flux parametrization used is from [10][11]. Variation in the production rates are expected when different flux parametrizations or different cross section databases are used. Changes up to 200% have been estimated. The expected number of events per tonne of material has been calculated for two cooling down scenarios after one year of activation at sea level. The estimated in-situ underground activation due to muon induced neutrons for the long lived, high Q-value isotopes at the SNOlab location, 2 km underground, is less than 1 event/(yr·t).

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Isotope	R_{surf} [μBq/kg]	$R_{\alpha,n}$ [μBq/kg]	R_{rock} [μBq/kg]
^{120m}Sb	159.13	3.84e-6	1.25e-6
^{125}Sb	205.59	3.46e-5	2.36e-6
^{127}Sb	165.46	4.66e-12	2.12e-6
^{129}Sb	83.83	1.05e-12	1.36e-6
^{125}Sn	4.21	7.02e-8	1.08e-7
^{118}Te	203.02	-	1.11e-6
^{121}Te	85.03	5.32e-3	1.41e-6
^{121m}Te	375.78	9.16e-4	3.39e-6
^{127m}Te	624.80	5.30e-2 +^{127}Sb	1.72e-5+^{127}Sb
^{129m}Te	507.61	1.89e-2	1.33e-5
^{121m}Sn	29.71	3.20e-7	2.56e-7
^{123}Sn	26.88	7.33e-7	2.39e-7
^{125}I	50.14	-	-
^{126}I	35.76	-	-
^{129}I	12.74	-	-

Table 5: Production rates for isotopes listed in table 2. R_{surf} is the production rate at sea level obtained with the ACTIVIA code for E>200 MeV and the TENDL-2009 database for E<200 MeV. $R_{\alpha,n}$ is the production rate at the SNOLAB location due to neutrons from (α,n) reactions in the norite rock after 50 cm attenuation [28]. Cross sections values are from the TENDL-2009 database. R_{rock} is the production rate due to μ-induced neutron flux at the SNOLAB location. Values are obtained using the ACTIVIA code for E>200 MeV and the TENDL-2009 database for E<200 MeV. The flux is from [29]. Where not specified the feeding isotope is already included.

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