Backgrounds by Cosmogenic Activation of Materials in DarkSide-20k with Geant4

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1. Introduction

Understanding the detector backgrounds is an essential step for successful WIMP detection in Darkside20k. The background rate is expected from muon-induced spallation of the detector materials. When cosmic-ray muons pass through the detector, they produce secondary particles, which then occasionally break argon nuclei and make other isotopes. Unstable daughter isotopes decay later emitting betas and neutrons, which can mimic the WIMP signals.

The physics of spallation isotope production by cosmic-ray muons is now better understood [1–5]. The most important concepts are as follows

1)Almost all isotopes are made by muon secondaries, not directly by muons.

(2) Almost all of these secondaries are made in showers, which are relatively rare along muon tracks.

(3) Almost all the isotope-producing secondaries are made in hadronic showers, which are even rarer. (11C, a dominant background isotope in oil, is made in electromagnetic showers.)

This means that we can tag the Argon volume (Outer Argon Veto, Neutron Argon Veto, TPC active Argon) in which the the isotope can be produced looking for the signal from muon (and/or shower) in the volume. For example if we see the high energy signal from muon or shower in TPC active Argon - this means that some isotope can be produced in this volume.

This report is devoted to the calculations of the Darkside background due to the cosmogenic isotopes production.

2. Cosmogenic muons and secondary particles flux in Hall C

Results of simulations performed by the DarkSide-50 collaboration in the Fluka Monte Carlo package were used to determine the muon and secondary particle fluxes in Hall C (see figures 1 and 2). These events were created by the muons when they traversed a 7 meters thick Gran-Sasso rock layer of HALL C [6]. The cosmogenic muon flux at Hall C equals $3.4 \cdot 10^{-4}$ $\mathrm{c}^{-1}\mathrm{m}^{-2}$ [6] and this number was used for time normalization of the Monte Carlo simulation results. Total time corresponds to ten years of Darkside20k data taking.

3. Modeling the production of β and $\beta - n$ isotopes in the Darkside-20k detector

As a result of the interaction of muons with the substances of the detector, radioactive isotopes can be produced and then contribute to the value of the total expected background of DarkSide-20k. The most dangerous are the $\beta - n$ isotopes emitting the neutrons. Such neutrons are elastically scattered on the detector target nuclei, thus imitating the detection of WIMP particles.

Calculations of isotope production by cosmogenic muons and their showers were made in the Geant4 package using the upgraded standard Monte Carlo code (called g4ds) from version 4.10.01 to the versions 4.10.5 and 4.10.6. Simulations with Geant4 versions

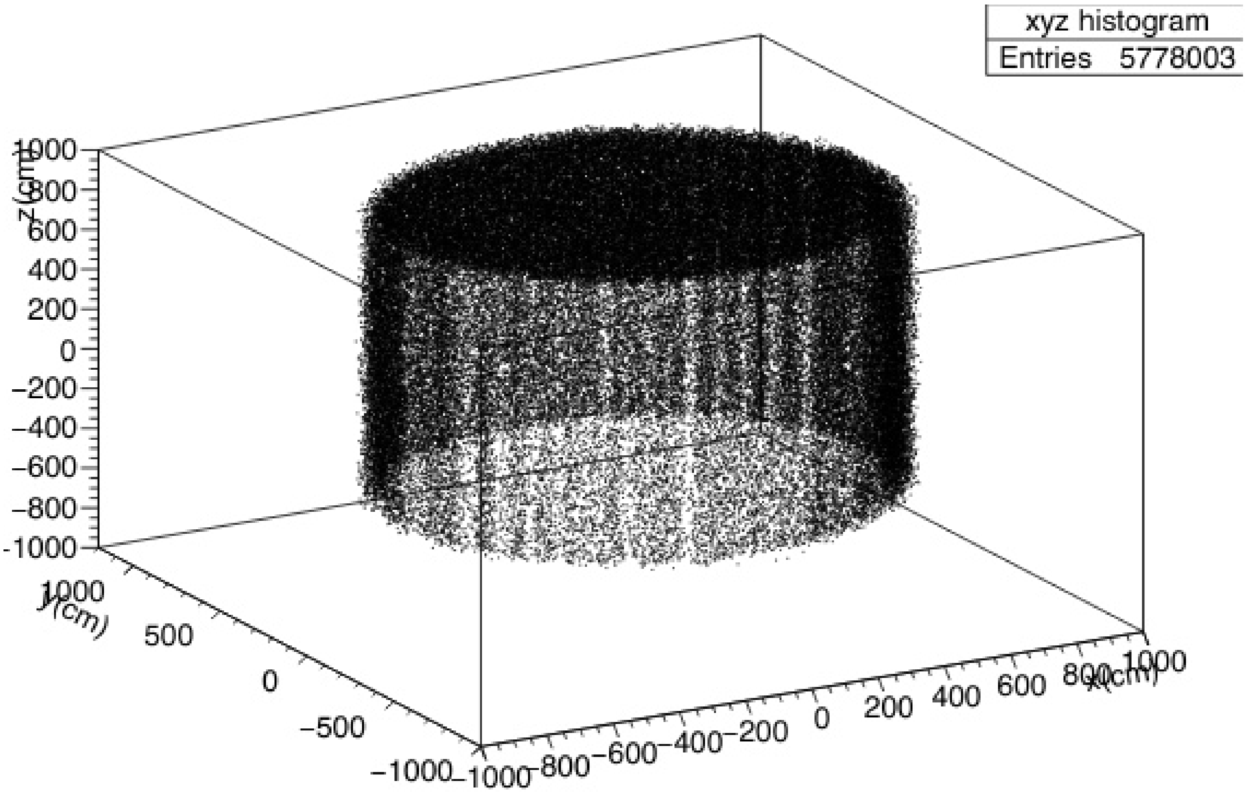


Figure 1: Location of incoming muons on the surface of a cylinder with a radius of 7 m and a height of 14 m in Hall C of the Gran Sasso Underground Laboratory.

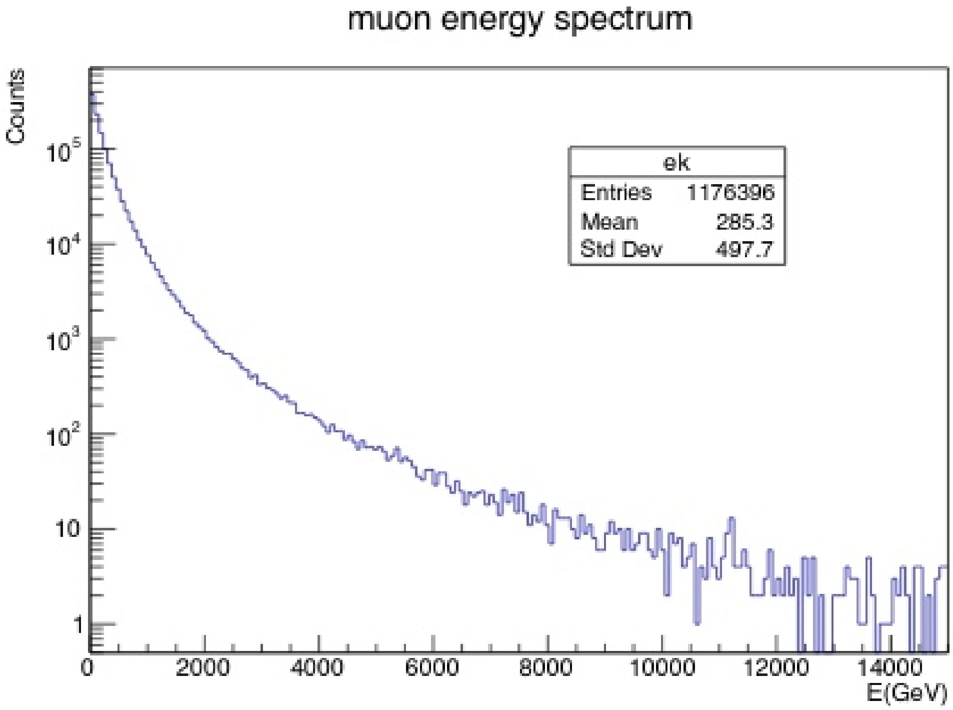


Figure 2: Muon energy spectrum in Hall C.

4.10.5 and 4.10.6 give the similar results. Two different physics list QGSP−BIC−HP and QGSP−BERT−HP were tested. We finally used the standard physics list QGSP−BIC−HP for isotope production, as far as it gives higher isotope production yields. The simulated statistics correspond to 10 years of data taking at Hall C.

The precision of predicting isotope yields, which is mostly limited by the uncertainties in hadronic processes, is typically a factor of ≈ 2. For example, in Super-Kamiokande [4], the `FLUKA`-predicted yields of some isotopes agree with measurements within a few tens of percent; some are off by a factor $\approx 2-3$. In Borexino [5], `FLUKA` predictions also agree well with experimental measurements. A few tens of percent agreement is found for some isotopes, but a factor of $2-4$ for some others. As for the predicted yields from `GEANT4`, a factor of ≈ 2 agreement with data is observed for some isotopes, while a few differ by a factor of ≈ 10. Overall, a factor of ≈ 2 precision is adequate as isotope yields usually differ by orders of magnitude. Because the decay time profiles and energy spectra are known from laboratory data, all that is needed is the yield constants. Theory is needed to get the predicted yields close enough to identify the key physical processes and to develop cuts. Finally it is necessary to note that these predictions can be refined with experimental measurements.

In the APPENDIX all $\beta - n$ isotopes, their main decay modes and lifetimes produced in three liquid argon volumes (TPC volume, Neutron Veto and Outer Muon Veto) are presented. 50 different $\beta - n$ isotopes can be generated by cosmogenic muons and their showers in all liquid argon DarkSide-20k volumes. As a result of the simulation we see that the production of isotopes is uniformly distributed inside the argon volumes of DarkSide-20k as far as for cosmogenic muons with 100 GeV energies the Darkside argon is the thin target. Thus the amount of isotopes is proportional to the mass of 3 different argon volumes in Darkside20k (TPC Argon, Neutron Veto Argon, Outer Veto Argon) with good accuracy ($<$10%). Using this fact the number of $\beta - n$ isotopes in the TPC volume (rather small one) for the cases of zero statistics of simulation was recalculated from the amount of the same isotope in all DarkSide-20k argon.

The most simple strategy for the rejection of beta-n events in DarkSide20k can be in using of the simple muon veto systems: if muon crosses the TPC Argon Volume or Neutron Veto Argon Volume it is tagged and in offline we can reject all the events within some seconds after the muon (also as to study such isotopes production). In the case of 100 % muon veto efficiency the main part of the produced short-lived $\beta - n$ isotopes decays will be rejected by Neutron Veto except for the long lived isotopes with high yields and lifetimes more than 0.64 s

The expected muon rate for TPC volume equals to 0.0065 Hz, for 5 seconds muon veto - the Darkside20k dead time will be equal to 3%. For comparison, according to the DarkSide20k Technical Design Report the Dead time of the Darkside20k detector due to Neutron Veto anticoincidences expected to be equal to 13% [7].

In tables 1 and 2 the resulting yields of the most dangerous $\beta - n$ isotopes produced in the TPC and Neutron Veto liquid argon volumes within 10 years of the DarkSide-20k data taking are presented. As it can be seen from the tables 1 and 2 the yield of $\beta - n$ isotopes is rather high even for the 5 s Veto time for cosmogenic muon crossing the Neutron Veto. In next chapters we calculate the acceptance of such events as WIMP particles after applying the DarkSide-20k WIMP search criteria.

Table 1: Yields of $\beta - n$ isotopes at TPC UAr in 10 years.

Isotope	$T_{1/2}$, s	Isotope Yield for TPC UAr	Neutron Yield for TPC UAr after 5 s Veto
^{16}C	0.747	1.15	0.011
^{17}N	4.173	20	8.28
^{22}O	2.25	2	0.0043
^{22}F	4.23	33	1.229
^{23}F	2.23	6	0.062
^{31}Al	0.644	93	0.00068
^{36}Si	0.45	12	0.00054
^{38}P	0.640	29	0.01548
Sum for 7 long lived isotopes		196.2	9.61
Sum for others isotopes		151.0	0.0139
Total Sum		347	9.62

4. Models for background decays of $\beta - n$ isotopes

Schemes of $\beta - n$ decays of the produced isotopes with the most unfavorable yields were investigated, using IAEA database [8], and the respective generators that simulate beta and neutron radiation were written and added to the Geant4 package. The resulting generators were integrated into the present version of the g4ds program. $\beta - n$ decay for one of the most active and long-lived isotope is shown in figure 3.

There are no reliable experimental data on $\beta - n$ transitions for other 7 main long-lived isotopes. Therefore, transitions were simulated, basing on the IAEA database [8]. The respective decay schemes are listed in table 3.

Table 2: Yield of $\beta - n$ isotopes at Neutron Veto UAr in 10 years.

Isotope	$T_{1/2}$, s	Isotope Yield for Neutron Veto UAr	Neutron Yield for Neutron Veto UAr after 5 s Veto
^{16}C	0.747	2	0.0191
^{17}N	4,173	34	14.077
^{22}O	2.25	3.2	0.00686
^{22}F	4,23	50	1.8621
^{23}F	2.23	12	0.1243
^{31}Al	0.644	159	0.0117
^{36}Si	0.45	19	0.00085
^{38}P	0.640	56	0.0299
Sum for 7 long lived isotopes		335	16.13
Sum for others isotopes		256	0.0016
Total Sum		591	16.1335

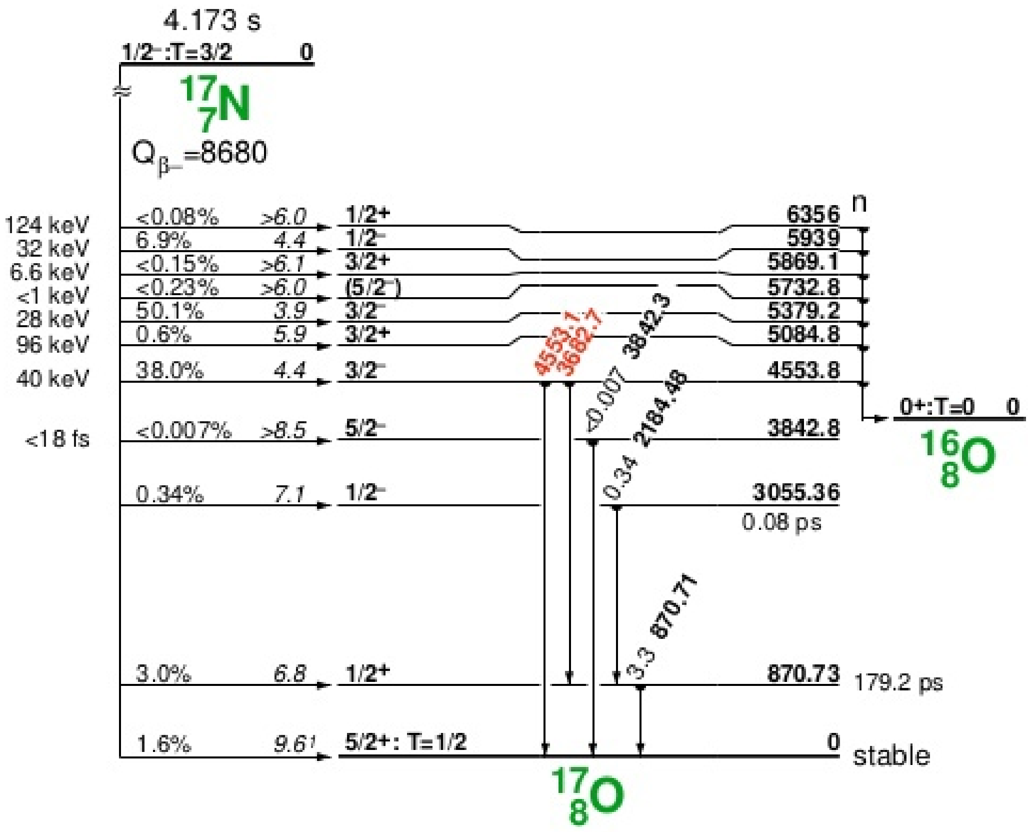
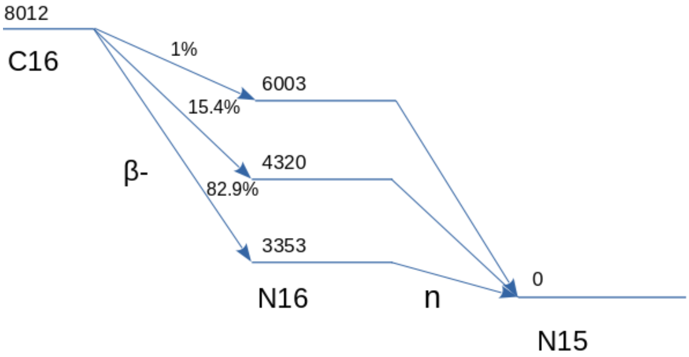
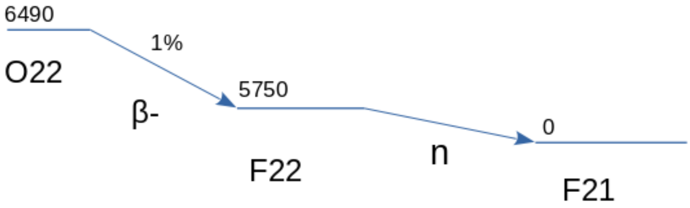
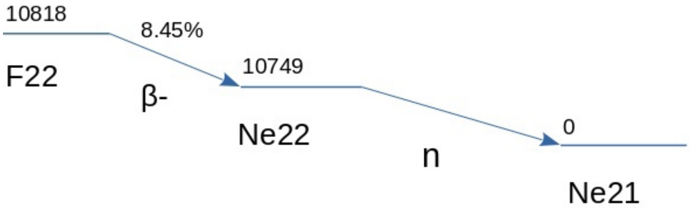
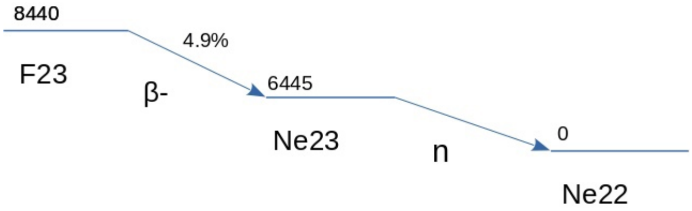
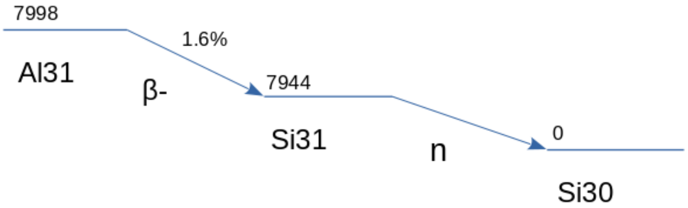
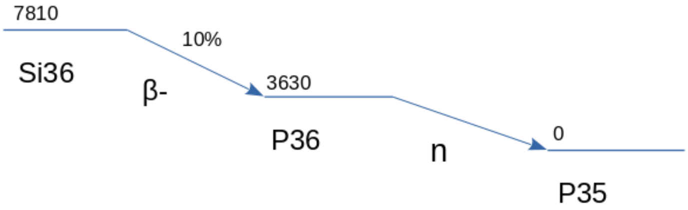
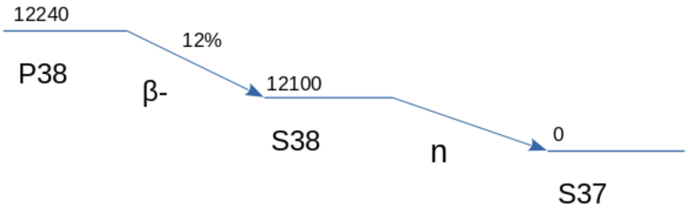


Figure 3: ^{17}N decay scheme.

Table 3: $\beta - n$ transition schemes for 7 main long-lived isotopes.

	$\beta - n$ transitions for the ^{16}C isotope. A neutron with an energy of 3294.5 keV is emitted from a level of 6003 keV; the 1716.7 keV neutron corresponds to the 4320 keV level and the 810.1 keV neutron is related to the 3353 keV level [9].
	$\beta - n$ transition of ^{22}O is shown, where $S_n = 5230$ keV, $E = 5750$ keV, energy of the emission neutron $E_n = 520$ keV.
	$\beta - n$ transition ^{22}F is shown, where $S_n = 10364$ keV, $E = 10749$ keV, energy of the emission neutron $E_n = 385$ keV.
	$\beta - n$ transition ^{23}F is shown, where $S_n = 5201$ keV, $E = 6445$ keV, emission neutron energy $E_n = 1244$ keV.
	$\beta - n$ transition ^{31}Al is shown, where $S_n = 6587$ keV, $E = 7944$ keV, emission neutron energy $E_n = 1357$ keV.
	$\beta - n$ transition ^{36}Si is shown, where $S_n = 3465$ keV, $E = 3630$ keV, emission neutron energy $E_n = 165$ keV.
	$\beta - n$ transition ^{38}P is shown, where $S_n = 8036$ keV, $E = 12100$ keV, emission neutron energy $E_n = 4064$ keV.

5. Rejection of neutron events from $\beta - n$ decays by the WIMP selection criteria in the TPC Argon Volume and Neutron Veto Argon Volumes of DarkSide-20k detector

The selection of WIMP-like events in the standard analysis of the DarkSide20k data is performed using the following criteria:

- nclusNR $= 1$
  (the number of the formed nuclear recoil clusters is equal to one)
- isFV30 $= 1$
  (the area of the cluster formation is limited by the central cylindrical volume with a mass of 30 t)
- abs(cl_z) < 100
  (the Z-axis coordinate of the cluster is less than 100 cm)
- $7.5 <$ cl_ene < 50
  (the energy range is from 7.5 keV to 50 keV)
- cl_elec $<$ cl_nucl
  (the scattering energy of electrons is less than the energy of nuclei)
- energyER < 50
  (the total energy released by clusters after neutron capture is below the 50 keV threshold in the TPC)
- late_eneVeto_Ar < 200
  (the total energy released by the clusters after neutron capture is below the 200 keV threshold in the Neutron Veto)

100000 events of $\beta - n$ decays of ^{16}C, ^{17}N, ^{22}O, ^{22}F, ^{23}F, ^{31}Al, ^{36}Si, and ^{38}P isotopes were simulated. The events were uniformly distributed in TPC and Neutron Veto liquid argon volumes and also in the center of the TPC for ^{17}N. The selection was made according to the WIMP event criteria described above. See tables 4 and 5 for further details.

It's worth noting that in cases of zero simulation statistics we conservatively estimate the rejection factor as if we have one final event in the simulations.In this calculation we assumed the 100% detection efficiency for the muons and showers, crossing the neutron Veto argon volume.

Table 4: Selection of WIMP-like events from $\beta - n$ decays by combined criteria for TPC Active Ar.

100000 $\beta - n$ events in Active Ar	^{16}C	^{22}O	^{22}F	^{23}F	^{17}N	^{17}N center TPC	^{31}Al	^{36}Si	^{38}P
(nclusNR == 1) && (IsFV30 == 1)	2509	3221	2655	1064	1642	923	534	13339	918
&& (abs(cl_z) < 100)	1468	1853	1459	597	905	831	294	9059	533
&& (7.5 < cl_ene) && (cl_ene < 50)	429	631	224	352	279	116	191	2	280
&& cl_elec < cl_nucl	424	631	209	351	278	113	184	<1	264
&& (energyER < 50) && (late_eneVeto_Ar < 200)	3	104	28	4	2	<1	29	<1	2

Table 5: Selection of WIMP-like events from $\beta - n$ decays by combined criteria for Neutron Veto Ar.

100000 normalsize events β,n in middle UAr	^{16}C	^{22}O	^{22}F	^{23}F	^{17}N	^{31}Al	^{36}Si	^{38}P
(nclusNR == 1) && (IsFV30 == 1)	353	329	279	366	806	389	193	371
&& (abs(cl_z) < 100)	222	212	177	226	712	238	117	241
&& (7.5 < cl_ene) && (cl_ene < 50)	17	5	2	15	104	17	<1	16
&& cl_elec < cl_nucl	17	5	2	15	102	17	<1	16
&& (energyER < 50) && (late_eneVeto_Ar < 200)	2	<1	<1	2	<1	2	<1	2

For the beta-n events, produced in TPC liguid argon the additional one criteria should be applied - mean distance between the first beta event cluster and the following cluster due to the neutron scattering on argon. In DarkSide20k we expect the recognition of 2 cluster with the distances > 2 cm. The elastic neutron crossection for 2 MeV neutrons (typical energy for beta-n neutrons, broadened within 10 keV due to kinematics of the decay) in Argon equals to 4 barn and weakly depends on the energy [10]. Thus the interaction length for such neutrons equals to 12 cm, and the number of unresolved beta and neutron clusters due to 2 cm spatial reconstruction is 14 %. This number should be checked with g4bx full simulation.

Combining the selection results with the neutron yields and taking into account the rejection by Muon Veto of 5 s, we obtain the final number of background neutrons in the DarkSide-20k detector with an exposure of 200 t · yr for the isotopes ^{16}C, ^{17}N, ^{22}O, ^{22}F, ^{23}F, ^{31}Al, ^{36}Si, and ^{38}P. Backgrounds from other short-lived isotopes is negligible due to the 5 s Neutron Veto.

Table 6: Final number of WIMP-like events from $\beta - n$ isotopes in TPC Active Ar in 10 years.

Isotopes	$T_{1/2}$, s	Isotope yield	n yield in active Ar	Number of n events after 5 s Veto	Final WIMP-like events
^{16}C	0.747	1.15	1.139	1.10E-02	9.84E-08
^{17}N	4.173	20	19	8.28	2.32E-05
^{22}O	2.25	2	0.02	4.29E-03	6.24E-07
^{22}F	4.23	33	2.78	1.23	4.82E-05
^{23}F	2.23	6	0.294	6.21E-02	3.49E-07
^{31}Al	0.644	93	1.488	6.85E-03	2.78E-07
^{36}Si	0.450	12	1.2	5.43E-04	7.60E-10
^{38}P	0.640	29	3.48	1.55E-02	4.32E-08
Total		196	29.4	9.61	7.27E-05

Table 7: Final number of WIMP-like events from $\beta - n$ isotopes in Neutron Veto Ar in 10 years.

Isotopes	$T_{1/2}$, s	Isotope yield	n yield in Neutron Veto UAr	Number of n events after 5 s Veto	Final WIMP-like events
^{16}C	0.747	2	1.98	1.91E-02	3.83E-07
^{17}N	4.173	34	32.3	14.08	<1.41E-04
^{22}O	2.25	3.2	0.032	6.86E-03	<6.86E-08
^{22}F	4.23	50	4.22	1.86E-01	<1.86E-05
^{23}F	2.23	12	0.588	1.24E-01	2.49E-06
^{31}Al	0.644	159	2.54	1.17E-02	2.34E-07
^{36}Si	0.450	19	1.9	8.59E-04	<8.6E-09
^{38}P	0.640	56	6.72	2.98E-02	5.98E-07
Total		335	50.3	16.13	< 1.63E-04

6. Total number of WIMP-like events in the DarkSide-20k TPC sensitive volume over 10 years of data taking

It is necessary to take into account the efficiency of the muon and showers tagging in the Darkside detector Veto system. Conservatively this number can be estimated as 0.9925 % using the experience of Borexino detector [5] located in the same Hall C of Gran-Sasso lab with approximately the same sensitive inner volume as Darkside 20k Neutron Veto. More simple considerations can be applied as the 0.1 second dead time of Neutron Veto electronics after the detection of high energies of the crossing muon and showers. In such case the detector misses Nmu·Tdead ≈ 0.0015 of cosmogenics events, where $Nmu \approx 0.015Hz$ is the rate of muons, crossing the Neutron Veto of Darkside 20k. In such case the efficiency of muon veto is 99.85 %. This number will be used for our final estimation.

a) Neutrons produced in TPC and Neutron Veto Argon Volumes

In case of the 5 s Neutron Veto time and 100% Neutron Veto dead time:

The number of WIMP-like events in the DarkSide-20k TPC sensitive volume over 10 years of data taking due to $\beta - n$ decays of cosmogenic isotopes in the TPC liquid argon volume equals $\approx 7.3 \cdot 10^{-5}$.

The number of WIMP-like events in the DarkSide-20k TPC sensitive volume over 10 years of exploitation due to $\beta - n$ decays of cosmogenic isotopes in the Neutron Veto argon volume is equal to $\approx 1.6 \cdot 10^{-4}$.

Thus the total number of WIMP-like events due to $\beta - n$ decays in the TPC and Neutron Veto volumes equals $\approx 2.4 \cdot 10^{-4}$ for 10 years in case of 5 s Neutron Veto time.

In case of the 5 s Neutron Veto time and 99.85% Neutron Veto efficiency for muons we miss for tagging some part of beta-n isotopes $N \approx 0.015 \cdot (N_{TPC} + N_{NeutronVeto}) \approx$

$\cdot$(347+591)$\approx$1.4.

For 8 long-lived isotopes after applying the rejection factor of WIMP search criteria the number of WIMP-like events equals to $\approx 2.5 \cdot 10^{-6}$.

Number of events from short-lived isotopes can be scaled from long-lived $\beta - n$ isotope events and equals to $\approx 4.3 \cdot 10^{-6}$. In such case the total number of missed in muon tagging WIMP-like events is negligible $\approx 6.8 \cdot 10^{-6}$. Exact simulation for the beta-n decays scheme of short-lived isotopes and their rejection by WIMP search criteria can be done in future for main short-lived isotopes.

Thus the total number of WIMP-like events for 10 years exposure from $\beta - n$ decays in 2 inner argon volumes (TPC and Neutron Veto Volume) taking into account the efficiency of Neutron Veto is $\approx 2.4 \cdot 10^{-4}$.

b) Neutrons produced in Outer Veto (Cryostate) Argon Volume

Neutrons from the decays of $\beta - n$ isotopes in the Outer Cryostat argon volume can not be tagged by the Outer Cryostat Veto due to their low $\beta -$decay energies. Total amount of neutrons produced in 10 years equals to 760. The results for Outer Argon Veto can be estimated using results for (alpha-n) production in Titanium vessel from the TDR report (as far as the produced neutrons have approximately the same energies of MeV scale). Total amount of neutrons produced in Titanium equals to 8800, after the rejection cuts this gives 2.1 $\cdot 10^{-3}$, rejection factor = 2.4 $\cdot 10^{-7}$. Rejection factor for neutron events produced by Radon alpha-n reactions in Outer Cryostate argon equals to 2.6 $\cdot 10^{-8}$. This rejection factor can be used also for the neutrons produced in beta-n decays, as far as the neutron energies are the simular one.

The total amount of WIMP-like events from beta-n isotopes in Outer Cryostate Volume using rejection factor for alpha-n neutrons from the Radon in cryostate argon equals to 1.4 $\cdot 10^{-5}$

It is necessary to note, that additional investigation for tagging such neutrons can be be done, using the shower nature of beta-n isotopes. The main part of $\beta - n$ isotopes are produced in showers with high energy, which can be detected by their energies also as by the multiplicity (detection in Outer Veto and Neutron Veto simultaneously). This can give additional factor of ten for the rejection.

7. Conclusion and plans for additional studies

The amount of WIMP like events from beta-n decays produced by cosmogenics muons and showers in liquid argon volumes $< \approx 2.6 \cdot 10^{-4}$.

This number can be refined, using Monte-Carlo simulutation with higher statistics, especially for the Neutron Veto argon volume.

Additional studies should be done for the possibility of Muon triggering in Neutron Veto. Marco Rescigno proposes to work without the Muon trigger in Neutron Veto. Instead it is possible "to provide the prompt window (say +-200 ns from the TPC trigger) to tag beta-N decays .

Additional work can be done for investigation of beta-n isotopes production in muon showers and their possible tagging by high deposited energy in argon and shower dimensions (coincidences between high energy events in Outer Veto, Neutron Veto and TPC). Additional reduction factor of 5-10 in the dead time is expected for the case of building the Outer (Cryostat) Veto.

8. APPENDIX

Underneath are the tables for beta-n isotopes and their neutron yields produced by cosmogenic muons and their showers within ten years in DarkSide liquid argon volumes.

Beta-n isotopes production by cosmogenic muons in DarkSide20k within 10 years

Isotope	Active Uar	Neutron Veto UAr	Outer LAr	All Ar	(β-,n)	(β-,2n)	(β-,3n)	Total number of neutrons	Number of neutrons in Outer LAr	Number of neutrons in Veto UAr	Number of neutrons in Active Uar	Half-life T1⁄2
P39	0,15	1	2	3,15	26,80%			0,844	0,536	0,268	0,040	282 ms
P38	29	56	343	428	12,00%			51,360	41,160	6,720	3,480	640 ms
Si37	3	3	21	27	17,00%			4,590	3,570	0,510	0,510	90 ms
Si36	12	19	115	146	10,00%			14,600	11,500	1,900	1,200	450 ms
Al36	0,1	0,32	2	2,42	31,00%			0,750	0,620	0,099	0,031	90 ms
Al35	1	6	15	22	38,00%			8,360	5,700	2,280	0,380	37,2 ms
Al34	4	3	28	35	26,00%			9,100	7,280	0,780	1,040	56,3 ms
Al33	6	12	72	90	8,50%			7,650	6,120	1,020	0,510	41,7 ms
Al32	23	43	256	322	0,70%			2,254	1,792	0,301	0,161	33 ms
Al31	93	159	1153	1405	1,60%			22,480	18,448	2,544	1,488	644 ms
Mg34	1	0,64	3	4,64	27,20%			1,262	0,816	0,174	0,272	20 ms
Mg33	1	1	8	10	14,00%			1,400	1,120	0,140	0,140	95 ms
Mg32	2	1	13	16	5,50%			0,880	0,715	0,055	0,110	86 ms
Mg31	1	1	26	28	6,20%			1,736	1,612	0,062	0,062	326 ms
Mg30	8	17	91	116	0,06%			0,070	0,055	0,010	0,005	313 ms
Na33	0,05	0,16	1	1,21	47,00%	13,00%		0,883	0,600	0,096	0,030	8 ms
Na32	0,05	0,16	1	1,21	24,00%	8,00%		0,484	0,320	0,051	0,016	12,9 ms
Na31	0,05	0,16	1	1,21	37,30%	0,87%	0,05%	0,474	0,382	0,061	0,019	17,35 ms
Na30	0,05	0,16	1	1,21	30,00%	1,15%		0,391	0,312	0,050	0,016	48,4 ms
Na29	1	1	7	9	25,90%			2,331	1,813	0,259	0,259	44,1 ms
Na28	3	4	36	43	0,58%			0,249	0,209	0,023	0,017	30,5 ms
Na27	13	30	188	231	0,13%			0,300	0,244	0,039	0,017	301 ms
Ne29	0,05	0,16	1	1,21	28,00%	4,00%		0,436	0,320	0,051	0,016	14.7 ms
Ne28	0,05	0,16	1	1,21	12,00%	3,70%		0,235	0,157	0,025	0,008	20 ms
Ne27	0,1	0,32	2	2,42	2,00%			0,048	0,040	0,006	0,002	31,5 ms
Ne26	0,85	2	15	17,85	0,13%			0,023	0,020	0,003	0,001	197 ms
F25	0,1	0,32	2	2,42	23,10%			0,559	0,462	0,074	0,023	80 ms
F24	2	5	19	26	5,90%			1,534	1,121	0,295	0,118	384 ms
F23	6	12	86	104	4,90%			5,096	4,214	0,588	0,294	2,23 s
F22	33	50	340	423	8,45%			35,744	28,730	4,225	2,789	4,23 s
O24	0,05	0,16	1	1,21	58,00%			0,702	0,580	0,093	0,029	77.4 ms
O23	0,35	1	6	7,35	7,00%			0,515	0,420	0,070	0,025	97 ms
O22	2	3,2	18	23,2	1,00%			0,232	0,180	0,032	0,020	2,25 s
N20	0,3	1	5	6,3	42,90%			2,703	2,145	0,429	0,129	136 ms
N19	0,5	2	8	10,5	54,60%			5,733	4,368	1,092	0,273	336 ms
N18	5	6	72	83	7,00%			5,810	5,040	0,420	0,350	619,2 ms

Beta-n isotopes production by cosmogenic muons in DarkSide20k within 10 years

N17	20	34	220	274	95,00%			260,300	209,000	32,300	19,000	4,173 s
C20	0,05	1	0,79	1,84	65,00%	18,50%		1,877	0,660	0,835	0,042	16,2 ms
C19	0,05	0,16	1	1,21	47,00%	7,00%		0,738	0,540	0,086	0,027	46.2 ms
C18	0,1	0,32	2	2,42	31,50%			0,762	0,630	0,101	0,032	92 ms
C17	0,25	0,8	5	6,05	28,40%			1,718	1,420	0,227	0,071	193 ms
C16	1,15	2	21	24,15	99,00%			23,909	20,790	1,980	1,139	747 ms
B15	1	2	9	12	93,60%	0,40%		11,328	8,460	1,880	0,940	9,93 ms
B14	9	9	53	71	6,04%			4,288	3,201	0,544	0,544	12,5 ms
B13	26	25	176	227	0,28%			0,636	0,493	0,070	0,073	17,33 ms
Be14	0,1	1	1	2,1	98,00%	0,80%		2,092	0,988	0,988	0,099	4,35 ms
Be12	4	3	41	48	0,50%			0,240	0,205	0,015	0,020	21,50 ms
Li11	1	3	6	10	86,30%	4,10%	1,90%	10,020	5,538	2,769	0,923	8,75 ms
Li9	25	50	371	446	50,80%			226,568	188,468	25,400	12,700	178,3 ms
He8	8	18	101	127	16,10%			20,447	16,261	2,898	1,288	119,1 ms
Total	347,5	591,2	3966,79					756,740	609,374	94,939	50,775	
Total long lived with T1/2 > 640 ms (red colour)	196,15	335,2	2296					413,720	334,022	50,289	29,409	
Total short lived with T1/2 < 640 ms (black colour)	151,35	256	1670,79					343,020	275,352	44,650	21,366	
Neutrons from (alpha-n) reactions for other volumes of Darkside20k									Titanium Vessel 8800	Veto Acrylic 2300	TPC Acrylic 1200	

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