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Radon contribution to single particle counts of the ARGO-YBJ detector

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HIGHLIGHTS

- The ARGO-YBJ experiment is an air shower detector for gamma ray astronomy of very large area.
- The ARGO-YBJ detector can work into two modes: single particle mode and shower mode.
- The work shows how natural radioactivity can influence the single particle counting.
- The paper shows how to evidence (and correct) the radon influence on the detector counting.

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A B S T R A C T

The ARGO-YBJ experiment is an air shower detector for gamma ray astronomy and cosmic ray studies with an energy threshold of ~500 GeV. Working in "single particle mode", i.e. counting the single particles hitting the detector at fixed time intervals, ARGO-YBJ can monitor cosmic ray and gamma ray transients at energies of a few GeV.

The single particle counting rate is modulated by the atmospheric pressure and temperature, and is affected by the local radioactivity from soil and air. Among the radioactive elements, radon gas is of particular importance since its concentration in air can vary significantly, according to environmental conditions. In this paper we evaluate the contribution of the radon daughter gamma ray emitters to the single particle counting rate measured by ARGO-YBJ. According to our analysis, the radon gas contribution is roughly 1–2%, producing a counting rate modulation of the same order of magnitude of the atmospheric effects.

1. Introduction

The ARGO-YBJ experiment, located at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l.), is a full coverage air shower detector devoted to gamma ray astronomy and cosmic ray studies, working with an energy threshold of ~500 GeV. Besides the shower triggered detection, ARGO-YBJ operates in "single particle mode", or "scaler mode", i.e. counting the single particles hitting the detector in fixed time intervals (Aielli et al., 2008). This technique allows to study temporal variations of the cosmic ray flux due to solar events like Ground Level Enhancements and Forbush decreases, and to search for short time duration excesses from Gamma Ray Bursts at primary energies above a few GeV (Aielli et al., 2009). In such a measurement, it is important to identify all the possible causes of counting rate variations due to local sources.

The single particle counting rate is modulated by the atmospheric pressure (that affects the shower propagation in the atmosphere) and the ambient temperature (that affects the detector efficiency). Beside these known effects, that in principle can be corrected, a fraction of the counting rate is due to gamma rays emitted by natural radionuclides (Cattaneo et al., 2009): a constant contribution from soil (and concrete floor) radioactivity under the ARGO-YBJ hall and a variable and less predictable one due to radon concentration in air.

In this paper we evaluate the effect of gamma rays from the decay of radon daughters. The data of radon measurements performed with different techniques at the experiment site will be correlated with the ARGO-YBJ counting rate and compared to the rate expected by simulating the radon activity in the ARGO-YBJ hall.

2. The ARGO-YBJ detector

The ARGO-YBJ detector consists of a 74×78 m^2 carpet made of Resistive Plate Chambers (RPCs) operated in streamer mode, with 92% of active area, surrounded by a partially instrumented (20%) area up to 100×110 m^2. The detector is divided into 153 logical units, called *clusters*, of area 5.7×7.6 m^2, each composed of 12 RPCs. The experiment layout is shown in Fig. 1, where the position of the radon monitors and the clusters used in this analysis are also marked. Details about the detector and the RPC performance can be found in Aielli et al. (2006).

The detector has two independent data acquisition systems: shower and scaler modes. In shower mode, showers with at least 20 particles firing the central carpet in a time window of 420 ns generate the trigger. The arrival times and positions of each particle are recorded, in order to reconstruct the core position and the arrival direction of the shower.

In scaler mode, for each cluster every 0.5 s the signals are added up and put in coincidence in a narrow time window (150 ns), giving the counting rates of $\geq$1, $\geq$2, $\geq$3 and $\geq$4 particles (referred in the following as C1, C2, C3 and C4, respectively). The counts, read by four independent scalers, have average rates ~40 kHz, ~2 kHz, ~300 Hz and ~120 Hz.

In a previous work (Aielli et al., 2008), in order to correct the counting rates for the atmospheric pressure P and the detector gas temperature T, we performed a fit with a two-dimensional function linear in P and T (as a first approximation). While for C2, C3 and C4 we found a barometric coefficient $\mu = -(0.9-1.2)$%/mbar, for C1 the value of μ was significantly lower, ranging from -0.3 to -0.5%/mbar, depending on the considered cluster and the experimental conditions. The thermal coefficient was the same ($\beta = 0.2-0.4$%/°C) for the four scalers.

To explain the lower C1 barometric coefficient we suppose that a consistent amount (50% or more) of C1 rate is due to soil and concrete floor radioactivity, that is not influenced by the ambient pressure. A fraction of this contribution, to be evaluated, is expected to be due to radon daughter gamma emitters. On the other hand, natural radioactivity should not affect the higher multiplicity channels, since the probability that $\geq$2 gamma rays hit the same cluster within 150 ns is negligible.

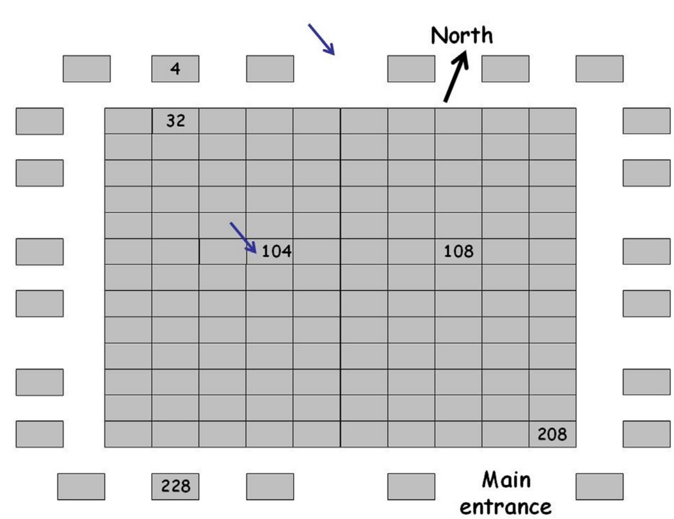

Fig. 1. Layout of the 153 clusters of the ARGO-YBJ detector. The numbers indicate the clusters used in this analysis, the thin arrows indicate the radon monitors (Lukas cells).

3. Radon gas concentration at the ARGO-YBJ site

Radon (^{222}Rn) is a noble gas belonging to the uranium (^{238}U) radioactive family. It is produced via the decay of ^{226}Ra and emanates from soil. It enters into buildings because it is an inert gas with a half-life of 3.82 days. It produces radionuclides emitting gamma rays able to influence the detector counting rate: ^{214}Bi and ^{214}Pb (BIPM, 2004). Because the radon progeny activity is approximately proportional to that of radon in air, in this work we study the influence of the radon concentration in the experiment hall air on the counting rates of the ARGO-YBJ detector.

We do not consider the thorn progeny since the experimental building structures (almost fully metal assembly and a unique concrete floor) suggest that the radon entry mechanism is mainly diffusion from soil and not from building materials or advection. Radon concentration is governed by a lot of variables in indoor environments, such as microclimatic conditions (i.e., wind, rain, temperature and pressure), building conditions (i.e. ventilation, state of the building itself, in particular the floor), soil characteristics (i.e. porosity) and geological movements (i.e. earthquakes) (NCRP, 1989; Humanante et al., 1990). Indoor radon time variations can be described by the following equation:

$$\frac{dC_{Rn}(t)}{dt} = \frac{E(t)}{V} - [\lambda + I(t)]C_{Rn}\left(t\right) \quad (1)$$

where: $C_{Rn}(t)$ is the radon concentration in indoor air at time t, $E(t)$ is the gas emission rate into the room of volume V, λ is the radon decay constant and $I(t)$ is the room air exchange rate (Nazaroff and Nero, 1988). Many studies show that indoor radon variations seem to be a chaotic phenomenon (Bejar et al., 1995). Radon indoor dynamic might be modelled as a function of meteorological parameters and of radon exhalation rate. This and newer models should require "closed and controlled environments" (Font and Baixeras, 2003; Jelle, 2012). In real situations, forecasting indoor radon concentration is difficult; for example, inside the ARGO-YBJ experimental room the air exchange rate term, $I(t)$, is unpredictable (highly variable). In fact, the room is not a "closed environment", since there are many big-circled holes on the walls equipped with fans to increase the ventilation rate for detector cooling and there is also one large door opened for car parking (and other activities).

Instead of modelling radon dynamics in the hall, ^{222}Rn concentration in the ARGO-YBJ experimental room is continuously monitored both at the detector centre and next to the North building wall (North side, in the following), 50 m apart (see Fig. 1).

The radon monitors are two Lucas cells (scintillation cells coated with zinc sulphide activated with silver) (Nazaroff and Nero, 1988), provided by MIAM srl, Italy, calibrated with a standard source of ^{226}Ra. The typical standard error of the Lucas cell technique is about 15%.

As expected, the measured radon concentration in the ARGO-YBJ hall air is highly variable. The monthly average concentration at the carpet centre is 300–500 Bq/m^3, depending on meteorological conditions, hall ventilation, etc. The concentration at the northern wall of the experimental hall shows even larger variations, reaching values up to 5000 Bq/m^3 in time scales of a few hours. During the period 2010 July 7–19, for example, the average radon concentration at the carpet centre was 450 Bq/m^3 with a standard deviation of 190 Bq/m^3 and extreme values 120–1060 Bq/m^3, while on the North side the average concentration was 860 Bq/m^3 with a standard deviation of 470 Bq/m^3 and extreme values 330–2500 Bq/m^3.

In Fig. 2 the North side and the detector centre data are shown for the period 2010 June 2–15. During some days the radon shows a similar behaviour in both sites (second part of the curve), while sometimes the two series are very different, with fast increases at North, where the radon concentration reaches values up to thousands Bq/m^3 in time scales of a few hours (first part of the same curve).

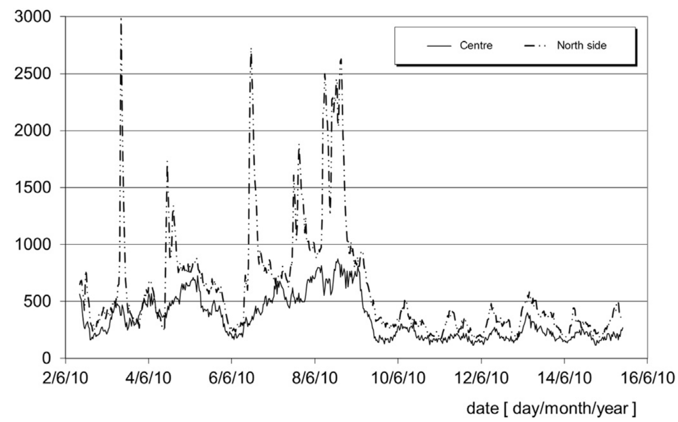

Fig. 2. Time sequence of radon concentration in air (Bq/m^3), measured at the detector centre (solid line) and on the detector North side (dashed line). The data sampling is every 0.5 h. The standard errors in radon measurements using Lucas cells are about 15%.

To confirm the data obtained with the Lucas cell detectors, three additional campaigns using passive nuclear track detectors (CR-39 type) have been carried out. Table 1 shows the average concentrations measured at different positions in the YangBaJing Cosmic Ray Laboratory area during the last campaign on 2010 July 7–20. The radon soil concentration close to the building North wall (outside) is found to be higher than that measured close to the South wall (last two rows of Table 1), confirming what has been observed inside: the concentration is much higher on the North side. These data suggests that radon mainly diffuses from that side and spreads within the hall where it is partly removed by ventilation (Bolognino et al., 2010, 2011). This is represented by the air exchange term in equation (1).

During the period from 2009 August 10 to September 27, we also investigated the radon spatial distribution above the detector carpet. Our results show a quasi-homogeneous distribution both horizontally and vertically, taking into account the standard deviation (~20%). In particular, in the horizontal plane (1 m above the carpet), the average radon concentration is 410 ± 110 Bq/m^3, ranging from 270 to 760 Bq/m^3. Also the vertical radon distribution (1, 2 and 3 m above the floor) does not show significant variations: the average concentration measured at the carpet center is 400 ± 70 Bq/m^3, ranging from 310 to 510 Bq/m^3.

Table 1
Radon concentration in air measured with CR-39 passive detectors at the YangBaJing Cosmic Ray Laboratory area from 2010 July 7 to 20. The average standard deviation is ~20%.

Position	^{222}Rn in air (Bq/m^3)
ARGO-YBJ building: CDC room (closed room)	950
Experimental hall: detector centre	380
Experimental hall: North side	530
Experimental hall: South side	430
Guest house: kitchen	300
Guest house: room A	410
Guest house: shower room	330
In soil, at North of the ARGO-YBJ building	2970
In soil, at South of the ARGO-YBJ building	880

We can reasonably assume that the ^{222}Rn at the carpet centre can be taken as the average radon concentration over the whole ARGO-YBJ carpet for time periods of hours, while the radon concentration varies much more abruptly on the North side (Giroletti et al., 2011).

4. Monte Carlo simulations

Searching for a possible radon influence on the ARGO-YBJ lowest multiplicity channel counts, we first simulate the response of the RPC detectors to the gamma rays emitted by the ^{222}Rn daughters, using the FLUKA code (Battistoni et al., 2007; Fassò et al., 2005). The detector efficiency has been evaluated simulating the gamma ray interaction with air and with the RPC components structure and assuming any particles entering the detector gas with an energy higher than the argon ionization potential is counted.

The simulation was performed assuming radon gas uniformly distributed in the air of the ARGO-YBJ hall and various progeny equilibrium factors. The studied equilibrium factor varies from 0.3 to 0.7, being this the typical range of clean and ventilated closed environments like the ARGO-YBJ experimental hall. The simulated efficiency has been compared with the experimental one measured with radioactive sources at the energies of 0.66 MeV (^{137}Cs) and ~1.25 MeV (^{60}Co) (Altieri et al., 2001; Angelone et al., 1995). The results show that the contribution to the *C1* counting rate due to the radon daughters is ~1 Hz per Bq/m^3 of ^{222}Rn gas concentration in the hall air. The simulation errors are about 3%. Although the simulations clearly show that the radioactive gas can influence the lowest multiplicity channel, this result has to be considered only as a rough estimate, because of the many unpredictable parameters influencing the *C1* counts, i.e. the equilibrium factor (radon progeny distribution inside the hall and their deposition over the detector) and the hall air exchange, as discussed in the previous section.

5. Results and discussion

The data analysed have been collected in different seasons of 2010 (from January 1 to February 28, from June 2 to 15, from October 1 to December 31) and on various clusters located in different positions inside the experiment hall (clusters 4 and 32 on the North side, clusters 104 and 108 at the center, clusters 208 and 228 on the South side).

The analysis is based on the following time series of experimental data *x(t):* radon concentration in air C_{Rn}, atmospheric pressure *P*, temperature of the detector gas *T*, scaler counts *C1*, *C2*, *C3* and *C4*. Since radon data are collected every 30 min, we averaged the data of scaler counts, temperature and pressure over the same time interval.

In this work, we used also the normal standard variable *x*(t)*, defined as follows:

$$x^*\left(t\right) = \frac{x(t) - \langle x(t)\rangle}{\sigma[x(t)]} \tag{2}$$

where *x(t)* is the experimental data at time *t*, *<x(t)>* and *σ[x(t)]* are the mean value and the standard deviation, respectively, both calculated over the whole examined period (typically of a few weeks). The normal standard variable *x*(t)* maintains the same behaviour as the original one *x(t)* and has mean equal to zero and standard deviation equal to one.

The analysis has been carried out with two different approaches: the method of linearization and the proportional method.

5.1. Method of linearization

Following the *method of linearization*, as the first approximation the cosmic ray contribution to the *C1* counts is assumed to depend linearly on both the atmospheric pressure *P* and the temperature *T*, according to equation:

$$C1(t) = a + b[P(t) - \langle P\rangle] + c[T(t) - \langle T\rangle] + C1_{RESIDUE}(t) \tag{3}$$

where *a* represents the average contribution from both cosmic rays and the detector background (supposed mostly influenced by the natural radioactivity of soil and concrete floor and assumed constant), <P> and <T> are the mean value of pressure and of gas detector temperature, while the residual term $C1_{RESIDUE}$ is expected to be proportional to the radon concentration C_{Rn} if radon is the main time-dependent counting rate contribution not due to cosmic rays. The coefficients a, b and c are determined by a linear fit on *C1(t)* as a function of pressure and temperature. The correlation coefficient between C_{Rn} and $C1_{RESIDUE}$ can be studied when the *C1* time variations produced by environmental phenomena other than radon are negligible and its value can demonstrate the influence of radon gas on the *C1* counting variations. Fig. 3 shows the comparison between the radon concentration measured at the carpet centre and the $C1_{RESIDUE}$, calculated by fitting the data of cluster 104, in the period from 2010 June 2 to 15, according to equation (3). The linear regression coefficient between radon concentration and $C1_{RESIDUE}$ is 1.6 Hz/(Bq/m^3), to be compared with ~1 Hz/(Bq/m^3) obtained with the FLUKA simulations, and the correlation coefficient is 0.93.

The method applied to other clusters gives slightly different results: the lower regression coefficient (0.7) between C_{Rn} and $C1_{RESIDUE}$ for the same period has been found for peripheral clusters. Concerning the North side measurements, such a behaviour is not surprising due to the radon fast variations registered at this position. At South, the clusters 208 and 228 are close to the two building entrances that influence the radon exchange on this side. Moreover the cluster 228 is covered with a layer of lead.

The results of this method for different clusters averaged over all the analysed periods are shown in Table 2. The linear regression coefficient is around 1 Hz/(Bq/m^3), depending on the cluster position. It is not easy to assess the uncertainty of this figure due to the high variability of the involved phenomenology mentioned in section 4. A conservative estimate, which takes into account both

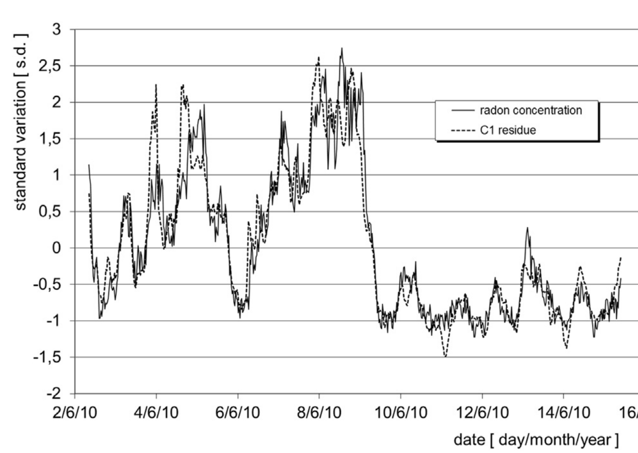

Fig. 3. Linearization method: relative variations of $C1_{RESIDUE}$ (dashed line) and of radon concentration measured at the detector centre (solid line). The variations are shown as normal standard variable according to equation (2). The data refers to the period 2010 June 2–15 and to the cluster 104.

Table 2
Results of the method of linearization applied to different clusters data. The second column gives the correlation coefficient between the radon concentration C_{Rn} (at the detector center) and $C1_{RESIDUE}$, the third the linear regression coefficient between $C1_{RESIDUE}$ and C_{Rn}. The errors are statistical.

Cluster#	Correlation coefficient	$C1_{RESIDUE}/C_{Rn}$ Hz/(Bq/m^3)
004	0.47	0.79 ± 0.04
032	0.58	1.02 ± 0.04
104	0.76	1.29 ± 0.03
108	0.77	1.18 ± 0.02
208	0.57	0.78 ± 0.03
228	0.42	0.71 ± 0.04

statistical and systematic effects, suggests an uncertainty of about 50%.

The analysis does not show any correlation between *C2*, *C3* and *C4* counts and the radon concentration in air both at the carpet centre and on the North side, as expected.

5.2. The proportional method

According to the *proportional method*, the *C1* counts are considered as the sum of various terms: cosmic ray contribution γ_1 to the rate of the lowest multiplicity channel, radon contribution kC_{Rn} and detector background *B* (mostly influenced by the soil and floor natural radioactivity and assumed constant), according to equation:

$$C1(t) = \gamma_1(t) + kC_{Rn}(t) + B \tag{4}$$

where *k* quantifies how much radon concentration in air contributes to the *C1* counts. In this way, the radon influence can be highlighted by subtracting from *C1* two terms: the cosmic ray contribution γ_1 and the background *B*. To avoid confusion between the $kC_{Rn}(t)$ term and the radon concentration $C_{Rn}(t)$, in the following $kC_{Rn}(t)$ will be replaced by $C1_{NET}(t)$. It is expected that cosmic rays contribute proportionally to all the multiplicity channels (γ_1, γ_2, γ_3 and γ_4) and the *P* and *T* dependence does not modify this proportionality. Then it is possible to write:

$$\gamma_1(t) = h_2\gamma_2(t) = h_3\gamma_3(t) = h_4\gamma_4(t) \tag{5}$$

Considering that the radon contribution to the *C1* counts is a few per cent and is negligible on the higher multiplicity channels, as the first approximation, the *average* ratio between the rates of different scalers due to cosmic rays can be quantified as $h_n = <[C1(t)-B]/Cn(t)>$, with $n = 2$, 3 and 4. Since the natural radioactivity acts only on *C1*, in absence of other physical phenomena influencing the higher multiplicity channels, it results $\gamma_2 = C2$, $\gamma_3 = C3$ and $\gamma_4 = C4$.

From equation (4) it is trivial to get the radon contribution $C1_{NET}(t)$ to the *C1* counting rate:

$$C1_{NET}(t) = C1(t) - \gamma_1(t) - B \tag{6}$$

where γ_1 is calculated according to equation (5) using the higher multiplicity channel series and $C1_{NET}(t)$ replaces $kC_{Rn}(t)$ in equation (4). The maximization of the correlation coefficient between $C1_{NET}(t)$ and $C_{Rn}(t)$ allows the assessment of the *B* value to be used in equation (6). The proportionality between the two series shows how much radon in air is affecting the *C1* channel, i.e. the proportionality coefficient *k* between radon concentration and $C1_{NET}(t)$.

Because of the properties of the normalized series calculated according to equation (2) and assuming a constant background, $C1_{NET}^*$ can be calculated by subtracting to $C1^*$ the higher multiplicity channels $C2^*$ or $C3^*$ or $C4^*$ equivalently:

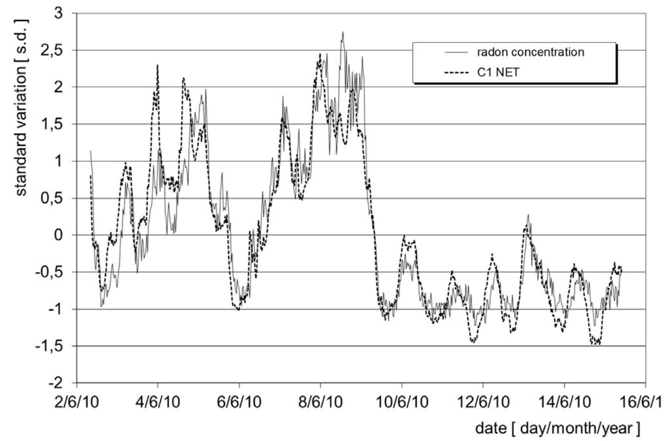

Fig. 4. Proportional method: relative variations of radon concentration at the detector centre (solid line) and of $C1_{NET}$ (dashed line) calculated using *C2* data according to equations (4) and (5). The variations are shown as normal standard variable according to equation (2). The data refers to the period 2010 June 2–15 and to the cluster 104.

$$C1_{NET}^*(t) = C1^*(t) - C2^*(t) = C1^*(t) - C3^*(t) = C1^*(t) - C4^*(t) \tag{7}$$

The correlation between the two series $C1_{NET}^*$ and C_{Rn}^* is expected to be high when only *P*, *T*, detector background *B*, radon and cosmic rays are influencing the *C1* counts. Equation (7) allow us to assess the radon influence on the *C1* counts also when the radon concentration was not yet measured (i.e. before 2009), in absence of physical phenomena influencing the detector counts other than *P*, *T*, cosmic rays and stable background.

The results of this analysis are shown in Figs. 4 and 5, where the normalized radon concentration at the detector center (cluster 104) is compared with $C1_{NET}$ for two different periods (2010 June 2–15) and (2010 October 1–17). Fig. 6 shows the correlation between $C1_{NET}$ and C_{Rn} relative to the same data of Fig. 5. The $C1_{NET}$ serie is calculated according to equation (6). The average ratio between (*C1*–*B*) and *C2* series is $h_2 = 9.8 \pm 0.4$, where a *B* contribution of about 24 kHz has been subtracted.

The evaluation of the *B* term is obtained by maximizing the correlation coefficient between the $C1_{NET}$ and C_{Rn} values. For the data shown in Figs. 4 and 5 the maximized coefficient is 0.92.

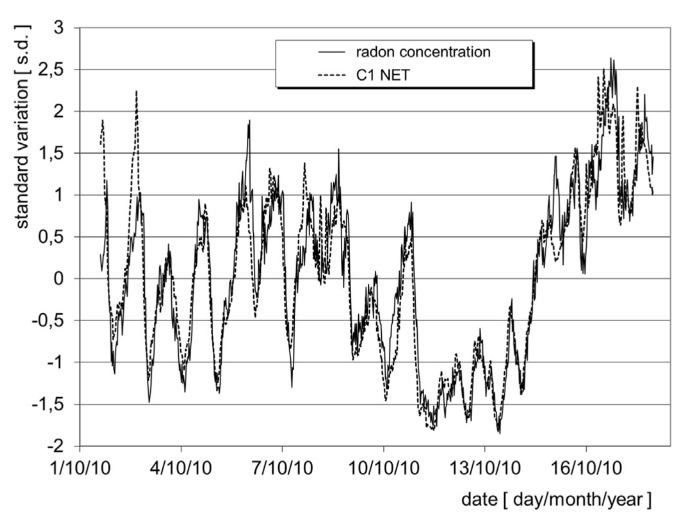

Fig. 5. The same of Fig. 4, for the period 2010 October 1–17.

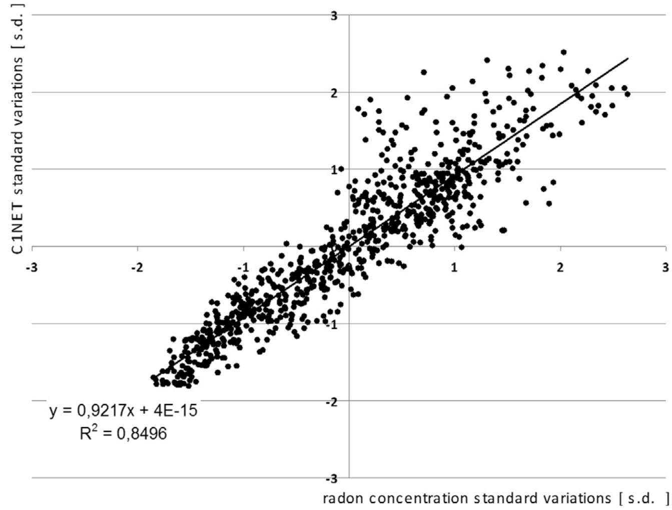

Fig. 6. Proportional method: $C1_{NET}$ versus radon concentration, for the period 2010 October 1–17. A linear fit is superimposed.

Similar results are obtained by correcting the *C1* signal with the other multiplicity scalers, either *C3* or *C4*. Concerning the linear regression coefficient between $C1_{NET}$ and C_{Rn} measured at the detector center, we obtain 1.65, 1.68 and 1.67 Hz/(Bq/m^3) when from *C1* we "proportionally" subtract *C2*, *C3* and *C4*, respectively.

In Table 3 the results obtained with this method are reported, averaged all over the analysed periods. Taking into account the large uncertainties affecting the data, these results appear fairly consistent with those obtained with the method of linearization. We note that this method is pointing out a *B* term of about 20 ± 5 kHz (depending on periods and clusters), in agreement with previous results (Aielli et al., 2008). This term is supposed to be due to the natural radioactivity of the soil and of the concrete floor.

Fig. 7 shows $C1_{NET}^*$ calculated subtracting $C2^*$ to $C1^*$ according to equation (7) and C_{Rn} (all in normal standard variable) for the cluster 104 (2010 January 1–31). A consistency between the time evolution of the two data sets is quite evident.

5.3. Discussion

The two methods used to investigate the correlation between the time variability of the *C1* counting rates and the radon concentration in air give consistent results, also when they are applied to time series of different seasons and clusters. In general, we obtain a remarkable correlation between the radon concentration C_{Rn} measured at the carpet centre and the "cleaned" *C1* signals ($C1_{RESIDUE}$ and $C1_{NET}$ series, depending on the applied method).

The correlation with the radon measured on the North side is in general worse because of the fast gas variations present in that position, but increases during periods without such a fluctuations. A poor correlation also exists when high atmospheric electric field variations are detected, like during thunderstorms (Salvini et al., 2011), suggesting that in this case physical variables other than *P*, *T*, cosmic rays, radon in air and soil natural radioactivity are affecting the scaler mode counting rates (Chilingarian et al., 2010) (a dedicated study is in progress).

The annual average radon concentration in the experiment hall, 300–500 Bq/m^3, is not trivial when compared to the workplaces reference level (300 Bq/m^3) adopted by the European Union in 2013 (European Union, 2014). Since the same researcher is working inside the experimental hall only few months per year, worker effective dose is lower than the annual dose limit stated for the population (1 mSv/year). For longer attendance periods inside the experimental hall, a specific risk assessment is suggested together with adequate provisions for reducing worker doses.

Table 3
Results of the proportional method applied to different clusters data. The second column gives the correlation coefficient between the radon concentration C_{Rn} (at the detector center) and $C1_{NET}$, the third the linear regression coefficient between $C1_{NET}$ and C_{Rn}. The errors are statistical.

Cluster#	Correlation coefficient	$C1_{NET}/C_{Rn}$ Hz/(Bq/m^3)
004	0.83	1.45 ± 0.03
032	0.89	1.43 ± 0.03
104	0.79	1.62 ± 0.05
108	0.78	1.01 ± 0.03
208	0.50	0.60 ± 0.04
228	0.54	0.70 ± 0.05

6. Summary and conclusions

The ARGO-YBJ experiment works in two detection modes: shower mode and scaler mode. In the scaler mode operation, the study of the four channels counting rates points out a different behaviour of the *C1* channel with respect to the higher multiplicity ones (*C2*, *C3* and *C4*). We ascribe this behaviour to the presence of the radon gas emanating from soil and diffusing inside the hall hosting the ARGO-YBJ detector. The radon decay produces radionuclides emitting gamma rays able to influence the detector counting rates.

The radon concentration is highly variable in time, as usual in indoor air environments. Its monthly average concentration at the detector centre is 300–500 Bq/m^3 and on the detector North side shows the greatest variations, reaching values up to 5 kBq/m^3 in time scales of a few hours. According to our findings, radon is entering mainly from the North side of the building.

In order to quantify the radon contribution to the ARGO-YBJ counting rates, we first carried out a Monte Carlo simulation and then applied two different methods of analysis of the experimental data, the method of linearization and the proportional method.

Both approaches give similar results, consistent with the simulations. According to our analysis, the radioactive gas in the hall air contributes to the *C1* counting rates for an amount of 0.6–1.7 Hz per Bq/m^3 of ^{222}Rn gas concentration measured in air at the

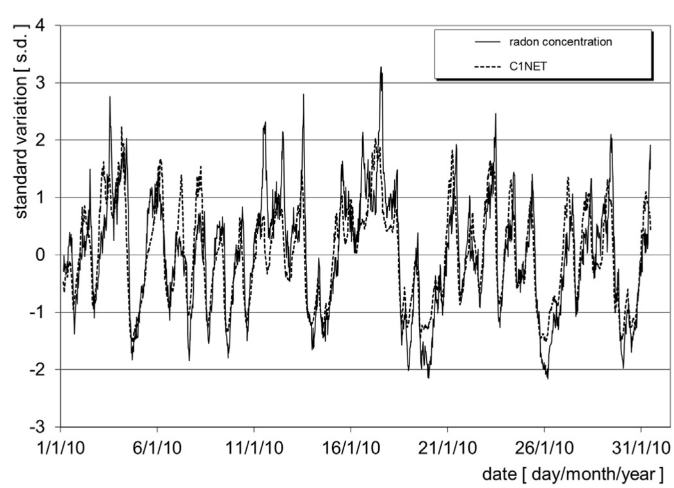

Fig. 7. Relative variations of radon concentration at the detector centre (solid line) and of $C1_{NET}^*$ (dashed line) calculated subtracting $C2^*$ from $C1^*$ according to equation (7) for cluster 104, for the period 2010 January 1–31.

detector centre. Considering a mean radon concentration of about 500 Bq/m^3, the gas average contribution to the *C1* counting rates (on average ~40 kHz) is roughly 1–2%, comparable to the effects of atmospheric pressure, −(0.9–1.2)%/mbar, and detector gas temperature, (0.2–0.4)%/°C. Some discrepancies between the data of different clusters are consistent with the strong variability, both in time and space, of the concentration of the radon gas and its daughters in the ARGO-YBJ hall air.

In addition, the second method of analysis (proportional method) points out a constant contribution of ~20 kHz to *C1*, probably due to the natural radioactivity present in the YangBaJing soil, as discussed in Cattaneo et al. (2009).

Finally, the higher multiplicity channels counting rates turn out to be unaffected by radioactivity from soil and air, as expected.

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