The phenomenon of neutron emission from earthquakes

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Abstract. Recent neutron emission detections have led to consider also the Earth's crust, in addition to cosmic rays, as a relevant source of neutron flux variations. Neutron emissions measured at seismic areas in the Pamir region (4200 m a.s.l.) exceeded the usual neutron background up to three orders of magnitude in correspondence to seismic activity and rather appreciable earthquakes, greater than or equal to the 4th degree in the Richter scale magnitude. The Authors present improved analysis with respect to that carried out by other research groups. The studies start from recent data acquired by Zanini et al. at the "Testa Grigia" Laboratory of Plateau Rosa, Cervinia, during an experimental campaign on the evaluation of neutron radiation from cosmic rays. Further data refer to a similar experimental campaign carried out in 1997 at Chacaltaya Laboratory in La Paz, Bolivia. The assessment of the neutron radiation at an environmental level could help to make a clear distinction between cosmic origin (cosmic rays) and the component from the Earth's crust (piezonuclear reactions). Moreover, taking into account the analogy between acoustic, electromagnetic emissions and seismic activity and also considering gas radon emission –that appears to be one of the most reliable seismic precursors– it will be possible to set up a sort of alarm systems that could be at the base of a regional warning network. This kind of warning system could combine the signals from other alarm stations to prevent the effects of seismic events and to identify the epicentre of an earthquake. Similar networks, only based on seismic accelerations, are being utilized all over the World in locations like Mexico, Taiwan, Turkey, Romania and Japan. Furthermore, neutron flux variations, in correspondence to seismic activity, may be an evidence of changes in the chemical composition of the crust, as a result of piezonuclear reactions.

Introduction

Monitoring the different forms of energy (Acoustic Emission AE, Electro-Magnetic Emission EME, and piezonuclear Neutron Emission NE), emitted during the failure of natural and artificial brittle materials, enables an accurate interpretation of damage in the field of mechanics of materials and fracture phenomena. The energy emissions have been mainly measured based on the signals captured by the acoustic emission (AE) measurement systems [1-5], or on the detection of the electromagnetic (EM) charge [6-13]. Nowadays, the AE technique is well-known in the scientific community and applied for monitoring purposes. In addition, based on the analogy between AE and seismic activity, AE associated with microcracks are monitored and power-law frequency vs. magnitude statistics are observed. The EM signals are related to brittle materials in which the fracture propagation occurs suddenly and it is accompanied by abrupt stress drops in the stress-strain curve. A number of laboratory studies revealed the existence of EM signals during fracture experiments carried out on a wide range of materials [6]. Moreover, it was observed that the EM signals detected during failure of materials are analogous to the anomalous radiation of geoelectromagnetic waves observed before major earthquakes [7], reinforcing the idea that the EM effect can be applied as a forecasting tool for seismic events. In fact, magnetic phenomena associated to earthquakes and volcanic eruptions have been studied all over the World utilising very sensitive instruments.

As regards the neutron emissions, original experimental tests were performed by Carpinteri et al. [14-18] on brittle rock specimens. Different kinds of compression tests under monotonic, cyclic and ultrasonic mechanical loading have been carried out fully confirming the hypothesis of piezonuclear reactions, giving rise to neutron emissions up to three orders of magnitude higher than the background level at the time of catastrophic failure of the specimens.

These phenomena have important implications also at the Earth's crust scale. Recent neutron emission detections by Volodichev et al. [19], Kuzhevskij et al. [20,21] and Antonova et al. [22] have led to consider also the Earth's crust, in addition to cosmic rays, as a relevant source of neutron flux variations. Citing Volodichev et al., neutron emissions measured in seismic areas of the Pamir region (4200 m a.s.l.) exceeded the usual neutron background «*up to two orders of magnitude in correspondence to seismic activity and rather appreciable earthquakes, greater than or equal to the 4th degree in the Richter scale magnitude*» [19]. Considering the altitude dependence of neutron radiation (Pfotzer profile [23]), values about 10 times higher than natural background at sea level are generally detected at 5000 m altitude. Therefore, the same earthquake occurring at sea level should produce a neutron flux up to 1000 times higher than the natural background. More recent neutron emission observations have been performed before the Sumatra earthquake of December 2004 [24]. Variations in thermal neutron measures were observed in different areas (Crimea, Kamchatka) a few days before that earthquake.

In this work measured neutron components exceeding the usual neutron background in correspondence to seismic activity are described. The studies start from recent data acquired at the "Testa Grigia" Laboratory of Plateau Rosa, Cervinia (Italy), during an experimental campaign on the evaluation of neutron radiation from cosmic rays [25-27]. In particular, the assessment of the neutron radiation at the environmental level could help to make a clear distinction between cosmic origin (cosmic rays) and the component from the Earth's crust (piezonuclear reactions).

By integrating all these signals (AE, EME and NE) –and also considering gas radon emission that appears to be one of the most reliable seismic precursors– it will be possible to set up a sort of alarm systems that could be at the base of a regional warning network. This kind of warning system could combine the signals from other alarm stations to prevent the effects of seismic events and to identify the epicentre of an earthquake. Similar networks, only based on seismic accelerations, are being utilized all over the World in countries like Mexico, Taiwan, Turkey, Romania and Japan [28].

Moreover, piezonuclear reactions related to the neutron emissions coming from active faults may be considered as the principal cause of magnesium depletion and the consequent carbon formation during seismic activity. In this way, CO_2 atmospheric level may be considered as an appreciable precursor, together with acoustic, electromagnetic and neutron emissions, before relevant earthquakes. Recently, significant changes in the diffuse emission of carbon dioxide were recorded in a geochemical station localized at El Hierro, in the Canary Islands [29], before the occurrence of several seismic events during the year 2004. Appreciable CO_2 emissions were observed before earthquakes of relevant magnitude and reaching maximum values some days before the most important seismic events.

Atmospheric Neutrons at High Altitude Observatories

Galactic cosmic radiation generates secondary ionizing particles in the atmosphere (Fig. 1a), that, together with primary protons, deposit a certain amount of dose. The most important radiation components are due to neutrons, electrons, positrons, protons, muons and photons. Usually the dose is varying in a complicated way with altitude and with geomagnetic coordinates (longitude and

latitude), being larger towards the Polar Regions and lower in the vicinity of the Equator. It also depends on the solar activity, which varies according to a cycle about 11 years long. Besides radiation components originating from the galactic cosmic radiation, the sun may occasionally add another component in connection with solar particle events (SPE) (Fig. 1b).
Classically the neutron energy distribution is influenced by the atmospheric composition: in fact, neutrons are mainly produced by the reaction of primary protons with atmospheric nuclei N (78%) and O (21%).

Atmospheric neutron measurements. Zanini et al. [25-27], during a period of more than 10 years (1997–2008) at High Altitude Observatories (HMOs) in the Northern and Southern Hemisphere, performed experimental campaigns to obtain information on the variability of atmospheric neutron spectra with solar activity. During the research activity in these laboratories, specific techniques for neutron spectrometry and dosimetry were set-up, suitable for being applied to different fields, such as aircrew exposure to Cosmic Rays (CRs) in high-altitude flights or in space missions. This confirms the relevance of the research activity at HMOs for the environment, space and health studies.
The experimental evaluation of neutron spectra in the wide energy range of interest and in the complex radiation field generated by the hadronic shower in the atmosphere, requires a special technique. This experimental technique, based on passive neutron detectors with different threshold and energy responses, allows the reconstruction of the neutron spectra in the energy range of interest. The results of neutron spectra measurements have been carried out with passive instruments coupled with the unfolding code BUNTO, while the monitoring of the integral neutron dose has been performed by a REM (Roentgen Equivalent Man) counter.

Neutron devices and unfolding code. The short range spectrometric system (from 10 keV to 20 MeV) is based on the passive Bubble Detector Spectrometer (BDS) (BTI, Ontario, Canada) [30]. It is constituted of polycarbonate vials filled with a tissue equivalent gel, in which tiny superheated liquid (Freon) droplets are dispersed. Neutrons interact with the gel and produce recoil charged particles, which give rise to the boiling of droplets. This leads to the formation of visible bubbles that are trapped within the gel; the number of bubbles is related to the neutron dose. Six different types of detector (with different chemical composition) are available; each of these corresponds to a different energy threshold (10, 100, 600, 1000, 2500, 10,000 keV).
The unfolding package BUNTO [31] was especially developed to process the responses of the wide and short range spectrometers. In order to get an appropriate solution from the system of Fredholm's equations, that are obtained from measurements affected by large experimental uncertainties, a special method has been introduced: it is based on the random sampling of unfolding data from a normal distribution, whose parameters (mean value and standard deviation) are the average experimental reading and the associated statistic uncertainty. The BUNTO final spectrum is the calculated mean of possible solutions of the unfolding procedure, weighted on the mean standard deviation. BUNTO fixes the maximum variation between the possible solution and the mean value within 20%: this is assumed as ‘‘percent error’’ on the experimental spectrum points.
As regards the monitoring of neutron dose, the ALNOR REM counter (neutron sensitivity from thermal energy to 17 MeV) is able to separate the contribution of low and high energy neutrons from the total ambient dose equivalent.
As an example in Fig. 2, typical neutron spectra in terms of neutron fluence rate obtained at Testa Grigia (geographical position: 3480 m a.s.l., 45°56′ N , 7°42′ E) during the experimental campaigns of November 1997, March 2003 and December 2007 by using the BDS Spectrometer, are shown. The neutron spectra were measured during different solar activity periods (mean sunspot number: 10–20/11/1997: 34; 24–31/03/2003: 88; 05–10/12/2007: 19; from the web site of National

Geophysical Data Center [32]). Due to different values of solar activity, the energy spectra show different fluence intensity and similar shape, as expected, with evidence of a main peak at about 1 MeV, the so called *evaporative contribution*.

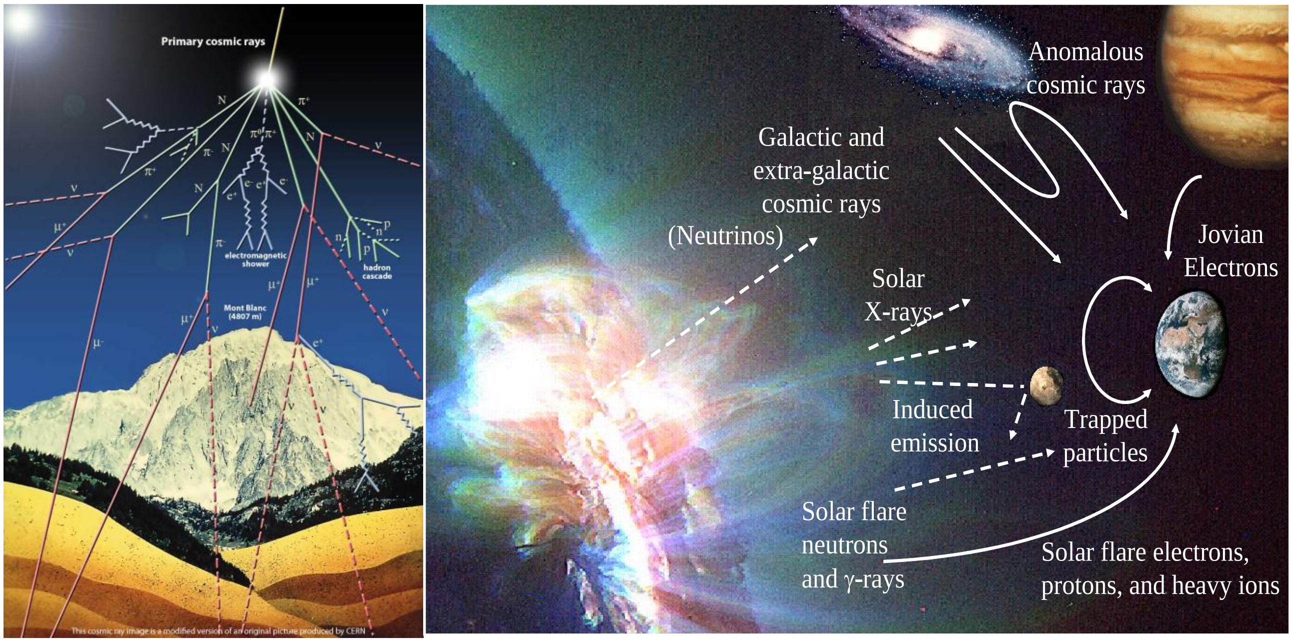

Fig. 1: (a) Radiation field generated by the hadronic shower in the atmosphere (left) (available at http://cosmicrays.le.infn.it). (b) Cosmic rays origin and composition (right).

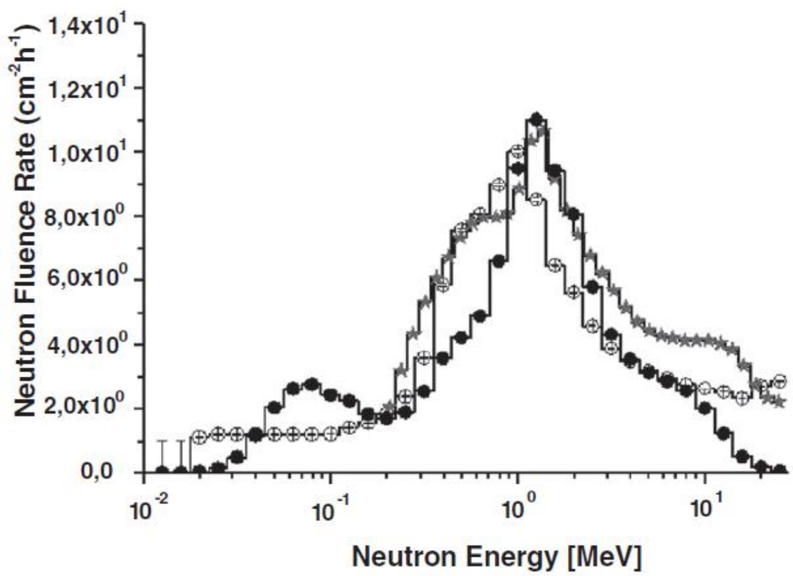

Fig. 2: Neutron spectra measured at Testa Grigia Laboratory during different solar activity periods (stars: November 1997; circles: March 2003; filled circles: December 2007), by using the BDS spectrometer (energy range 10 keV – 20 MeV) [25].

Piezonuclear Reactions: From the Laboratory to the Earth's Crust Scale

The confirmation that the environmental neutron component is linked to neutrons coming from galactic events but also from piezonuclear reactions, was assessed during experimental tests conducted at Politecnico di Torino on different types of brittle rocks [14-18]. In particular, neutron emission measurements, by means of He^3 devices and neutron bubble detectors, were performed during three different kinds of compression tests: (i) under displacement control, (ii) under cyclic loading and (iii) by ultrasonic vibration. The materials used for the tests were Luserna stones, basaltic rocks, Carrara Marble, Magnetite and mortar enriched with iron dioxide.

During compression tests on specimens characterized by brittle behaviour and sufficiently large size the neutron flux was found to be up to three orders of magnitude higher than the background level at the time of catastrophic failure. For test specimens with more ductile behaviour, neutron emissions significantly higher than the background were also found. Neutron detection is also confirmed in compression test under cyclic loading and during ultrasonic vibration. As an example, in Fig. 3a and 3b the load vs. time diagram, and the neutron count rate evolution for a Luserna stone and magnetite specimens are shown.

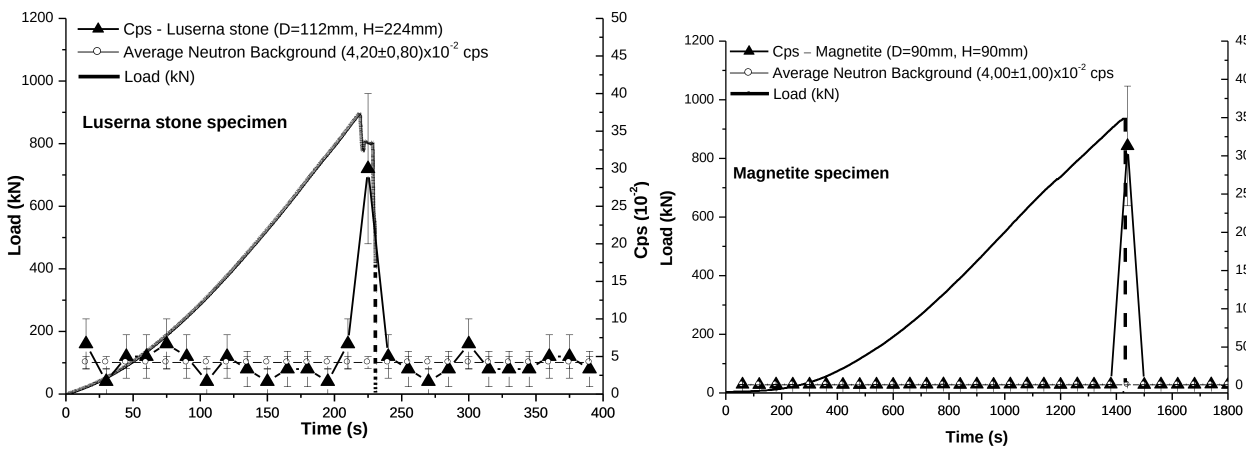

Fig. 3: (a) Luserna stone (left) and (b) Magnetite (right) specimens. Load vs. time diagrams, and neutron emissions count rate.

Since the analyzed material contains different amounts of iron, the conjecture of Carpinteri et al. [14-18] is that piezonuclear fission reactions involving fission of iron into aluminum, or into magnesium and silicon, should have occurred during compression damage and failure. This hypothesis is confirmed by Energy Dispersive X-ray Spectroscopy (EDS) tests conducted on Luserna stone specimens.

From the results and the experimental evidence reported in recent papers [14-18], it can be clearly seen that piezonuclear reactions are possible in inert non-radioactive solids. From the EDS results on fracture samples, the evidences of Fe and Al variations on phengite lead to the conclusion that the piezonuclear reaction:

$$Fe^{56}_{26} \rightarrow 2\,Al^{27}_{13} + 2\ \text{neutrons} \qquad (1)$$

should have occurred [14-18, 33,34]. Moreover, considering the evidences for the biotite content variations in Fe, Al, Si, and Mg, it is possible to conjecture that another piezonuclear reaction, in addition to (1), should have occurred during the piezonuclear tests [14-18]:

$$Fe_{26}^{56} \rightarrow Mg_{12}^{24} + Si_{14}^{28} + 4 \text{ neutrons} \quad (2)$$

Taking into account that granite is a common and widely occurring type of intrusive, Sialic, igneous rock, and that it is characterized by an extensive concentration in the rocks that make up the Earth's crust (≈60% of the Earth's crust), the piezonuclear fission reactions expressed above can be generalized from the laboratory to the Earth's crust scale, where mechanical phenomena of brittle fracture, due to fault collision and subduction, take place continuously in the most seismic areas.

Neutron Emissions from Earthquakes

As regards the observations performed by Zanini et al. [25-27], in the period from July 30 to August 3, 2008 an additional experimental campaign was conducted at the Testa Grigia laboratory. These measures were done to integrate those held in December 2007. Neutron monitoring was carried out by means of the short range bubble detector spectrometer (BDS) and the REM ALNOR counter. During the data acquisition an evident increase in neutron radiation was monitored between the July 31 and August 1st. This variation was detected in real time by the REM counter and later confirmed by the analysis of bubble dosimeters unfolded by BUNTO code. An increase of about 6 times of the neutron dose rate with respect to the average natural background was observed (Fig. 4a). This phenomenon was monitored for a period of about two hours. Then the values decreased to the usual background level. Moreover, the subsequent estimation of the neutron energy spectrum (Fig. 4b) showed the detection of the anomalous event. In addition to the usual evaporative peak, at about 700 keV – 1 MeV, a considerable high-energy neutron component of about 8 MeV was monitored. The fact that two different instruments, with different acquiring data methods, monitored simultaneously the same anomaly excludes any type of malfunction of the instrumentation. As usual, the assumptions made for the explanation of this event have firstly focused on possible effects of cosmic origin. However, from the analysis of data relating to solar and galactic events, apparently, no possible explanation for an event of such great intensity was found. In fact, no significant sunspot activity was recorded during the data acquisition time window. As well as, during the same period, no anomalies in the cosmic ray flux were detected (Fig. 5) [35]. This is also demonstrated by the data acquired at the laboratory of Jungfrajoch (geographical position: 3450 m a.s.l., 46° 32' N, 7° 59' E), a few hundred kilometres away from the Testa Grigia laboratory.

On the other hand, considering the phenomenon of neutron emission before earthquakes, a searching of earthquakes occurred in the immediate vicinity of the laboratory in the weeks following the experimental campaign was carried out. A discrete seismic activity [36] was observed during the period July-August 2008 in a region a few hundred kilometres away from the laboratory (Table 1). In particular, about 20 days after the anomalous increase in neutron radiation, a seismic event of the 3rd degree in the Richter scale of magnitude occurred about 130 km away. This interpretation is consistent with the observations of Kuzhevskij et al. [20, 21] and it provides further experimental evidence of the correlation between neutron emission and seismic events of appreciable intensity. Furthermore, the anomalous neutron emission and seismic activity being occurred in a granitic geographical area strengthens the piezonuclear hypothesis, as well as experimentally observed previously at the laboratory scale.

Moreover, a similar event, monitored in the Southern Hemisphere at the Chacaltaya Laboratory of La Paz, Bolivia (geographical position: 5230 m a.s.l., 16°35′ S , 68°12′ W) in November 1997, led to analogous results. Also in this case an anomaly of about an order of magnitude in the neutron flux was detected and, as in the case of Testa Grigia Laboratory, no plausible explanation of a cosmic or galactic origin was found. Then, searching seismic events in the areas in the immediate vicinity of the Bolivian laboratory, brought to find, at a distance of about 300 km, earthquakes of intensity comprised between 4.2 and 6.7 degrees in the Richter scale of magnitude [36] (Table 2).

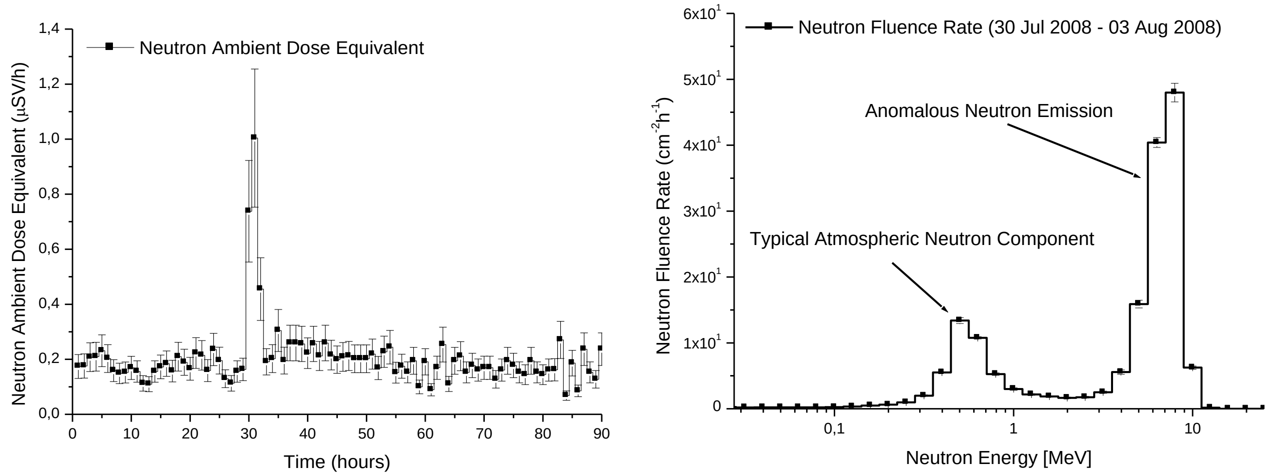

Fig. 4: (a) Neutron Ambient Dose Equivalent (left) measured by REM ALNOR counter at Testa Grigia Laboratory during the experimental campaign of July-August 2008. (b) Neutron spectrum (right) measured by using the BDS spectrometer (energy range 10 keV – 20 MeV).

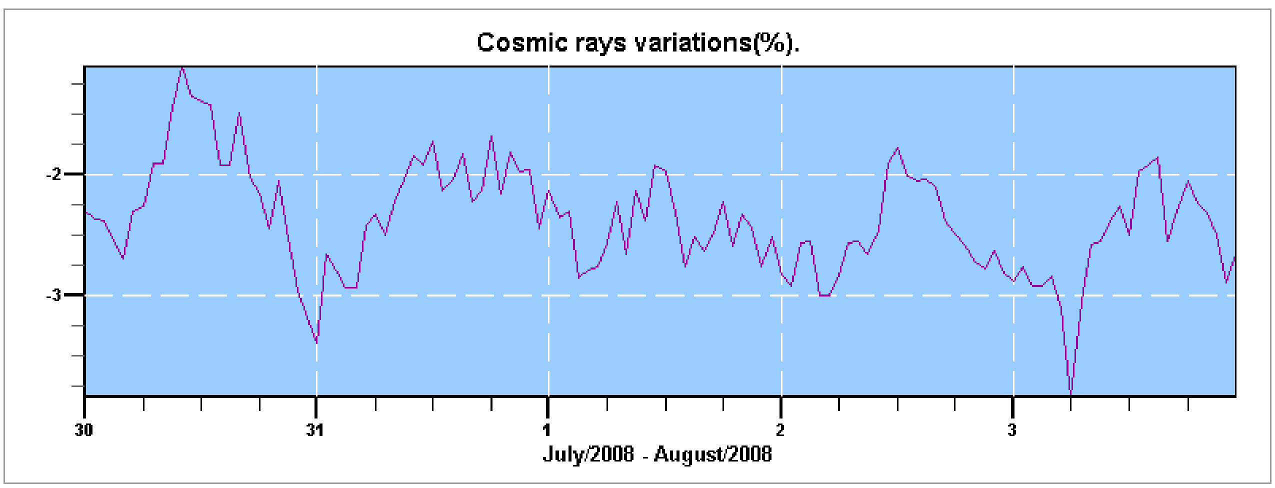

Fig. 5: Cosmic rays variation acquired at the laboratory of Jungfrajoch [35].

Table 1: seismic activity in the surrounding area of Testa Grigia laboratory in August 2008 [36]. It is also reported the distance between the earthquake epicenter and the laboratory.

Testa Grigia Laboratory – geographical position: 3480 m a.s.l., 45°56′ N , 7°42′ E						
YEAR	MONTH	DAY	LATITUDE	LONGITUDE	MAGNITUDE	DISTANCE
2008	08	10	44°18′ N	7°15′ E	2.7	199 Km
2008	08	14	44°43′ N	7°19′ E	2.8	171 Km
2008	08	20	44°78′ N	7°30′ E	3.0	131 Km
2008	08	21	46°65′ N	8°47′ E	2.5	99 Km
2008	08	21	44°86′ N	6°62′ E	2.9	145 Km

Table 2: seismic activity in the surrounding area of Chacaltaya laboratory in November – December 1997 [36].

Chacaltaya Laboratory – geographical position: 5230 m a.s.l., 16°35′ S , 68°12′ W						
YEAR	MONTH	DAY	LATITUDE	LONGITUDE	MAGNITUDE	DISTANCE
1997	11	28	13°74′ S	68°79′ W	6.7	263 Km
1997	12	06	17°26′ S	69°95′ W	4.5	249 Km
1997	12	25	19°02′ S	69°07′ W	4.2	352 Km

Conclusions

Starting from recent experimental data acquired at the "Testa Grigia" Laboratory of Plateau Rosa, Cervinia (Italy), further analyses –besides those already known in literature [19-22]– were presented to confirm the hypothesis that the Earth's crust, in addition to cosmic rays, is a relevant source of neutron flux variations. This phenomenon seems to take place several days before a significant seismic activity in the monitored areas occurs.

On the other hand, the confirmation that the environmental neutron component is also connected to neutrons coming from piezonuclear reactions was assessed during experimental tests on brittle rocks under mechanical stress, conducted at the Politecnico di Torino.

In this way a clear distinction, at the environmental level, between the neutron component of cosmic origin (cosmic rays) and that coming from the Earth's crust (piezonuclear reactions), in the assessment of the neutron radiation is possible.

Finally, taking into account the demonstrated close connections between acoustic, electromagnetic emissions and seismic activity, it will be possible to set up a sort of alarm systems that combine AE, EM and neutron sensors for the prediction and diagnosis of earthquakes.

These sensors could be applied at certain depths in the soil, along the most important faults, or very close to the most seismic areas to prevent well in advance the effects of seismic events and to identify the epicentre of an earthquake.

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