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# Neutron spectrometry at various altitudes in atmosphere by passive detector technique(*)

A. Zanini($^1$), C. Ongaro($^2$), C. Manfredotti($^1$), L. Tommasino($^3$)
and P. Miranda Losa($^4$)

($^1$) *INFN, Sezione di Torino - Via P. Giuria 1, 0125 Torino, Italy*
($^2$) *Dipartimento di Fisica Sperimentale, Università di Torino*
*Via P. Giuria 1, 0125 Torino, Italy*
($^3$) *ANPA - Via Vitaliano Brancati 48, Roma, Italy*
($^4$) *UMSA, Universitad Mayor de San Andres -La Paz, Bolivia*

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**Summary.** — A new experimental system, constituted by passive detectors, has been developed to measure neutron spectra at various altitudes in the atmosphere. The knowledge of the neutron spectrum is required to evaluate with a good accuracy the neutron contribution to the total dose, due to the cosmic ray exposure, in fact the flux-to-dose conversion factors strongly depend on neutron energy. Moreover, in many dosimetric applications, as the dose evaluation to the aircrew in service on intercontinental flights, the passive system is not only the most convenient but it is often the unique technique. The experimental system is constituted by the passive bubble detector BD100R, polycarbonate foils, polycarbonate bottles, sensitive in low and intermediate neutron energy range, and the bismuth stack, sensitive in the high energy range. Experimental data were obtained in high mountain measurements at Matterhorn (3600 m altitude, 46 N ) and Chacaltaya (5230 m altitude, 16 S), during flights at 12000 m and on board of stratospheric balloons at 38000 m.
All the spectra obtained show, as expected, the evaporation peak around 1 MeV and the second direct bump around 100 MeV; the results, different in the neutron flux intensity, confirm the satisfactory sensitivity of this experimental technique.

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## 1. – Introduction

The galactic cosmic radiation (GCR) interacts with the atmosphere to produce a secondary radiation, consisting of a neutron component and an ionising component. Neutrons are produced mainly from primary proton interaction with the atmosphere nuclei (nitrogen and oxygen) and from decays like

$$\Lambda \rightarrow \mathrm{n} + \pi^0; \qquad \Sigma^+ \rightarrow \mathrm{n} + \pi^+; \qquad \Sigma^- \rightarrow \mathrm{n} + \pi^- . \tag{1}$$

The energy distribution and the flux intensity of neutrons at various altitudes strongly depend on latitude (geomagnetic field) and solar activity (SCR modulated on the 22 years solar cycle) [1]. The neutron energy spectrum is characterized by a fast neutron component due to the evaporative production (with a Maxwellian energy distribution peaked at about 1 MeV and isotropic angular distribution) and by a faster neutron component due to the direct production (with an energy distribution peaked at around 100 MeV and anisotropic angular distribution). Neutron radiation is a high LET radiation, that is difficult to shield especially in conditions of limited space and weight. In addition, from recent epidemiological studies on bomb A survivors (Hiroshima and Nagasaki), the International Commission on Radiological Protection in the publication ICRP 60 [2] has pointed out the increased risk associated to neutron exposure. As a consequence neutron radiation must be considered more biologically damaging than previously assumed and new flux-to-dose conversion factors are proposed [3]. Moreover, an urgent need is recognized to a better estimation of cancer risk from low level of radiation. Since the human activities involving the exposure to cosmic ray radiation have been increasing in the last years (high altitude commercial flights, shuttle flights, medical and biological research on spatial stations), an accurate neutron dosimetry is required. To this aim the knowledge of the neutron spectrum is fundamental because the flux-to-dose conversion factors are strongly dependent on neutron energy. A neutron spectrometric system completely based on passive detectors and covering a wide energy range from few keV to many GeV has been especially developed for such applications. The use of a passive system is forced by the necessity of reduced volume and hence, no electronic and informatic supply as required in many of such activities. This spectrometric technique, applied to the equivalent dose evaluation at different altitudes and latitudes, represents a unique tool for neutron spectra evaluation in the cosmic ray field.

## 2. – Experimental method

A method for the evaluation of medium and high energy neutron spectra form 100 keV to many GeV was developed, based on a set of passive detectors (superheated drop detectors, polycarbonate and bismuth passive track detectors [4,5] and an unfolding code, BUNTO, especially written [6]). Due to the characteristics of passivity and insensitivity to photons, this spectrometric system can be used in mixed neutron and photon fields.
*BD100R* (*energy range:* 100 keV–20 MeV). The detector consists of a polycarbonate vial filled with elastic tissue-equivalent polymer; superheated freon drops are dispersed inside the gel. The interaction between incident neutrons and polymer causes a secondary charged particle emission; the consequent energy deposition generates bubble formation, due to the metastable state of freon. The number of bubbles trapped in the polymer, proportional to the neutron fluence, is recorded (BTI).

*Polycarbonate detector* (1 MeV–100 MeV). A large area stack consisting of $15 \times 15$ cm$^2$ polycarbonate foils. Damage tracks of recoil products from neutron interaction are detected with electroetching techniques.

*Polycarbonate bottle detector* (1 MeV–100 MeV). The vials of bubble detector are themselves polycarbonate detectors that can be used with the same procedure previously described.

*Fission* $^{209}$Bi *detector* (100 MeV–100 GeV). A stack consisting of layers of $^{209}$Bi deposited on 100 $\mu$m thick mylar film were realised for high energy neutron detection. The fission fragments from the interaction of high energy neutrons with $^{209}$Bi produce holes in mylar that can be detected by means of a spark counter. This new device has been developed in the ANPA laboratories [5] and it represents a suitable tool for monitoring the high energy component of the neutron field.

## 3. – Calibration

The calibration has been performed at CERN. The calibration of the passive detector system has been performed at the T14 position, H6-SPS beam at CERN. The neutron spectrum has been previously evaluated by Monte Carlo simulation [6] and it is characterized by two peaks located, respectively, at about 1 MeV and 100 MeV, *i.e.* similar in shape to the cosmic ray neutron spectrum. The passive detector results unfolded with the BUNTO code, are compared with the MC simulation and the experimental measurement obtained in the same location with the Bonner sphere system [7, 8]. The passive detector results are consistent with the MC simulation.

## 4. – Experimental measurements

Evaluation of neutron spectra has been performed in 4 different experimental conditions:

1) Testa Grigia Laboratory, Plateau Rosa, Cervinia, Italy (3600 m, 46 N),
2) Chacaltaya Laboratory, Chacaltaya, LaPaz, Bolivia (5230 m, 16 S),
3) Intercontinental flight Milano-Los Angeles-Milano (12000 m),
4) Balloon flight Trapani-Siviglia, ASI Trapani Base, Italy (38000 m).

*High mountain measurements*

The experiment 1 and 2 have been performed both in high mountain laboratories, at two different latitudes and altitudes to evaluate the sensitivity of the experimental method. In fact the neutron flux is characterized by strong altitude dependence and varies with the latitude, being maximum at the magnetic poles and minimum at the equator (by a factor of three to ten), in consequence of the geomagnetic field. The data have been collected in the same period of solar activity ('97-'98) to allow the comparison. The bubble detectors were exposed during 30 days, while the stack detectors, because of their characteristics, were exposed for a longer period to obtain a significant statistic (8 months).

*Testa Grigia experiment* (3600 m a.s.l., 46N). A preliminary data collection at Testa Grigia Laboratory (CNR, Matterhorn Italy) was performed in '95 and the experimental results were compared with the MC simulation in similar conditions with a good agreement [6, 9]. The new results confirm the previous ones in shape and intensity. The new

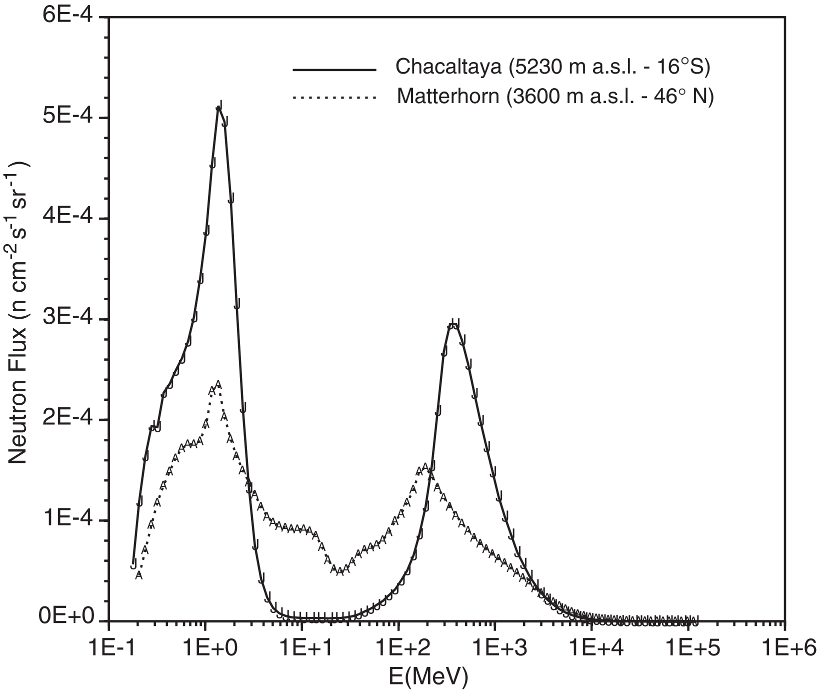

Fig. 1. – Neutron spectrum at Chacaltaya compared with the measured one at Matterhorn.

spectrum shows, as expected, the evaporation peak around 1 MeV and the second direct bump around 100 MeV.

*Chacaltaya experiment* (5230 m a.s.l., 16S). The same technique was applied for measurements at the Chacaltaya Laboratory (UMSA Universitad Mayor de San Andres, La Paz, Bolivia). Because the bubble detector response depends on temperature and pressure, the detectors BD100R were maintained at atmospheric pressure in a pressurized box; a temperature correction was also applied to the experimental data, according to the factory recommendations. In fig. 1 the comparison is shown between the neutron spectra obtained at Chacaltaya and at Matterhorn. The shape of the two spectra is similar in the position of the evaporation and knock-on peaks, while the intensity of the neutron flux in Chacaltaya is about 20% higher than in Matterhorn. Further investigation should be necessary to confirm this difference.

*Measurement on high altitude flight Milano-Los Angeles-Milano* (12000 m).

The passive detector system was allocated on board of an aircraft flying on the path Milano-Los Angeles-Milano at a cruise altitude of about 12000 m a.s.l. (bubble detectors were activated only at the cruise altitude). At this quote neutron dose equivalent represent about 60% of the total dose to aircrew; the main contribution is due to neutrons with energies between 0.1 and 20 MeV (produced in the evaporation peak region). In addition, a large fraction of the flux consists of neutrons with greater energies, produced in the knock-on region, and increases the neutron contribution to the total dose. As a consequence, the knowledge of neutron spectrum is of crucial importance for an accurate dosimetric evaluation. In fig. 2 the spectrum measured on board with the passive detec-

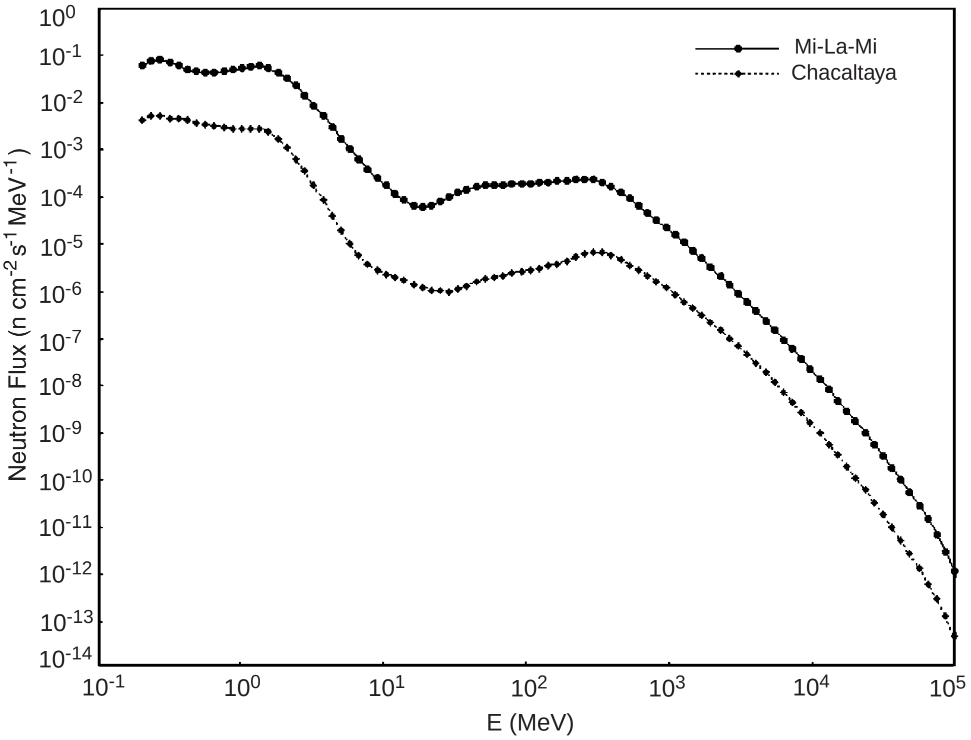

Fig. 2. – Neutron spectrum measured on Milano-Los Angeles-Milano flight path compared with the measured one at Chacaltaya.

tor system is compared with the spectrum measured at Chacaltaya. The two spectra are similar in shape; the position of the two peaks is consistent.

*Balloon flight Trapani-Siviglia* (38000 m a.s.l.). The passive dosimetric technique was recently applied in a balloon stratospheric flight launched from ASI Trapani Base (Agenzia Spaziale Italiana). The aim of this launch is the evaluation of the cosmic radiation effect on biological samples in view of application in space life. The accurate knowledge of the different components of the cosmic radiation and their contribution to the total dose is therefore essential as well as the use of instrumentation reduced in size and weight and suitable for different kind of radiation. In particular, for the neutron component, the possibility of measuring the spectrum is crucial in a dosimetric evaluation because of the wide neutron energy range and the strongly energy dependence of the flux-to-dose conversion factors. In this experiment, a new passive neutron spectrometer BDS has been tested.

*BDS spectrometer (BTI)* (10 keV–20 MeV). The passive neutron spectrometer BDS allows to obtain neutron spectra in terms of fluence as a function of neutron energy. It consists of a set of bubble dosemeters; by varying the gel composition and the thermodynamic conditions, 6 different detectors are realised, each one with a different energy threshold and energetic response. The total energy range extends from 10 keV to 20 MeV.

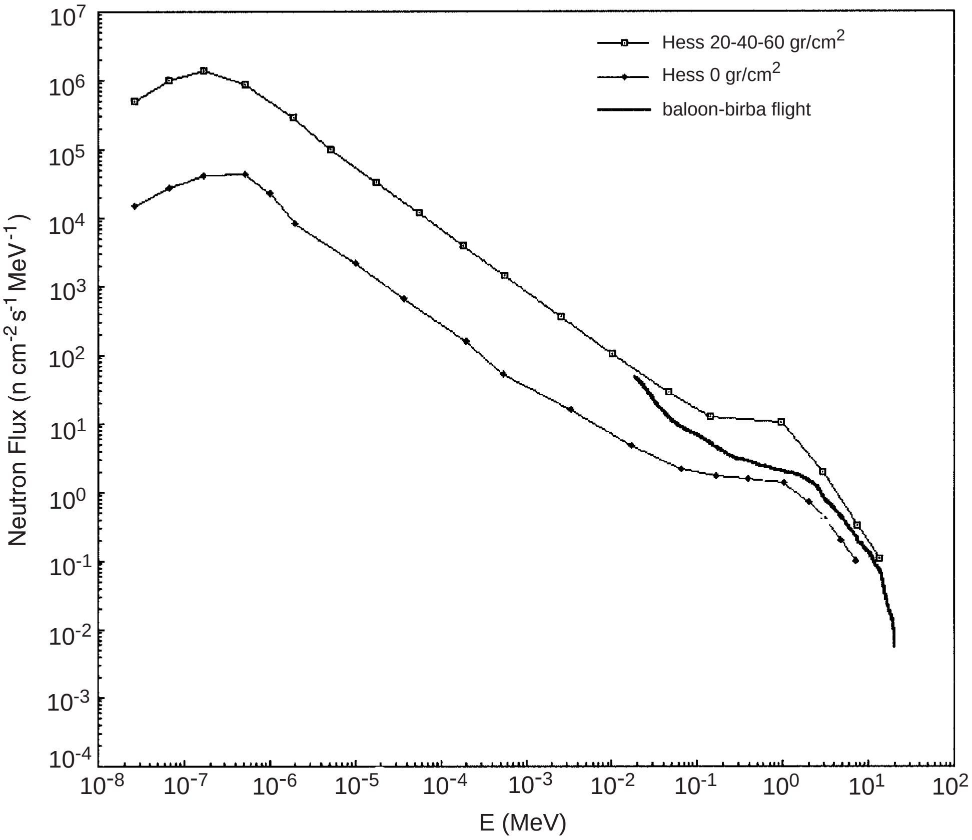

Fig. 3. – Neutron spectrum measured on balloon flight (3 g/cm$^2$) compared with Hess's calculations at corresponding altitudes [10].

The dosimetric system is sensitive to low doses, insensitive to gamma rays and responds to the request of reduced size and of friendly use. The neutron spectrum is then obtained by processing the experimental data with the unfolding code BUNTO. In fig. 3 the neutron spectrum measured during the balloon flight (38000 m a.s.l.) from Trapani (Italy) to Siviglia (Spain) is represented; the flight time, 22 hours, does not allow to obtain significative data on the high energy region by using the bismuth detector, which requires a long exposure time. As a consequence the spectrum is measured from 10 keV to 20 MeV (the BDS energy range). The spectrum is compared with the curves calculated by Hess [10] at corresponding altitudes. In the common energy range, the BDS curve (3 g/cm$^2$) is consistent with the reference curves at 0 g/cm $^2$ and 20 g/cm$^2$ and shows the evaporative peak.

## 5. – Conclusion

A complete spectrometric system, based on passive detectors, was developed for neutron dosimetry in a wide energy range. Experimental spectra are obtained in various conditions (high mountain in two hemisphere, high altitude commercial flight, stratospheric balloon flight), with satisfactory agreement if compared with simulation results and literature data. It must be stressed that neutron spectrometry, which is difficult to carry out because of the wide energy range and the associated photon field also in nuclear physics laboratories, represents a challenge in extreme conditions like the measurements on board of aircrafts or spatial stations. Therefore, the high dose rate from cosmic radiation associated with higher operating altitudes of civil and military flights and space missions, requires a suitable procedure of dosimetric monitoring for aircrew and astronauts. This detector set is the unique system completely based on passive detectors able to evaluate neutron spectra in a wide energy range, and can represent a useful tool for dosimetric evaluation in special conditions, in which sophisticated devices equipped by computer and electronic are not available. The intrinsic uncertainty of the system (20%) is acceptable for dosimetric purposes.

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