Revista Mexicana de Física
ISSN: 0035-001X
rmf@ciencias.unam.mx
Sociedad Mexicana de Física A.C.
México

Varela, A.; Policroniades, R.; Murillo, G.; Moreno, E.; Chávez, E.; Huerta, A.; Andrade, E.; Ortiz, M.E.
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Revista Mexicana de Física, vol. 57, febrero, 2011, pp. 93-96
Sociedad Mexicana de Física A.C.
Distrito Federal, México

Design and construction of an extended range bonner spectrometer

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Recibido el 10 de marzo de 2010; aceptado el 31 de agosto de 2010

In this work we describe the design and construction of an extended range Bonner Sphere Spectrometer (BSS) intended to be used in the measurement of the energy spectra of neutrons produced by cosmic radiation. A single BSS spectrometer designed and constructed by us, has been used for a long time as neutron monitor at the tandem accelerator of the National Institute for Nuclear Research (ININ, Mexico). The extended spheres added are 10 and 6 inch diameters with copper, bismuth and lead as inner shells. The measurements are to be initiated at the Physics Institute UNAM Mexico (IFUNAM) and at the Mexican Nuclear Center, near 3000 meters high.

Keywords: cosmic-ray neutrons; Bonner sphere spectrometer; neutron detector

En este trabajo se describe el diseño y la construcción de un espectrómetro de Bonner extendido (BSS) el cual va a ser usado en la medida del espectro de energía de los neutrones producidos por la radiación cósmica. Un espectrómetro de Bonner convencional diseñado y construido en el laboratorio del acelerador tándem del ININ, se ha usado como monitor por mucho tiempo y al cual se le han agregado esferas extendidas de 10 y 6 pulgadas de diámetro con cascarones de cobre, plomo y bismuto, dentro del polietileno. Las medidas estan por ser iniciadas en el Instituto de Física de la UNAM y en el Centro Nuclear de México a una altura aproximada de 3000 metros.

Descriptores: Neutrones cósmicos; espectrómetro Bonner; detector de neutrones rápidos.

PACS: 29.30.Hs

1. Introduction

In 1960, Bonner *et al.* described [1] the development of a neutron spectrometer, which consists of a set of polyethylene spheres with diameters of 2, 3, 5, 8 and 12 inches. In the center of these spheres a small ^{6}LiI(Eu) crystal is fixed, having 4 mm in diameter and 4 mm thick and 96% enriched in lithium-6. The neutrons are detected after being moderated in the polyethylene spheres, taking advantage of the high value of the ^{6}Li cross section for thermal neutrons.

Figure 1 shows total neutron cross sections for the ^{6}Li(n,α)^{3}H reaction, which, as noted presents high values for thermal neutrons, together with other neutron cross sections processes, relevant for neutron detection at small energies.

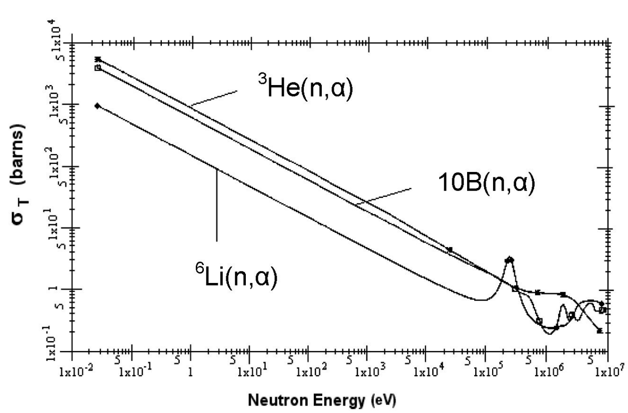

FIGURE 1. ^{3}He(n,p), ^{10}B(n,α) and ^{6}Li(n,α) cross sections as a function of incident neutron energy.

Taking into account the scattering events involved in a moderation process, it is clear that the neutron spectrometer will be more efficient for higher energy neutrons by using large polyethylene sizes, while, on the other hand, if the size of the polyethylene sphere is lower, then the efficiency gains will be biased toward thermal energy neutrons. This is proved by observing Fig. 2, which shows the response curves obtained by Bonner using mono-energetic neutrons in the energy range of 0.05 to 15.1 MeV.

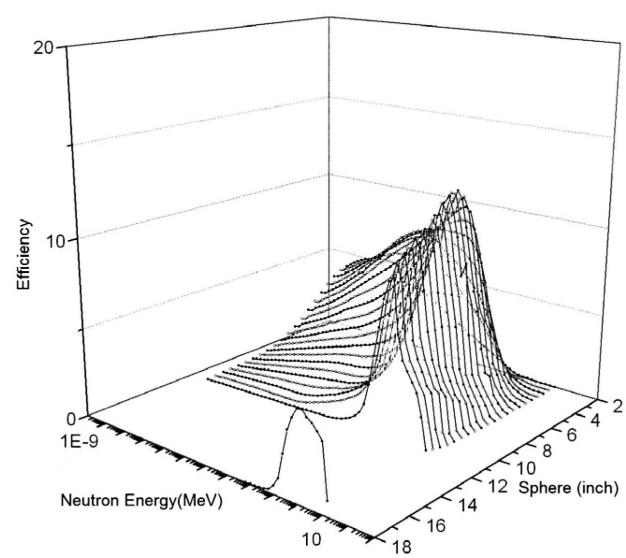

FIGURE 2. Overall response for all spheres giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

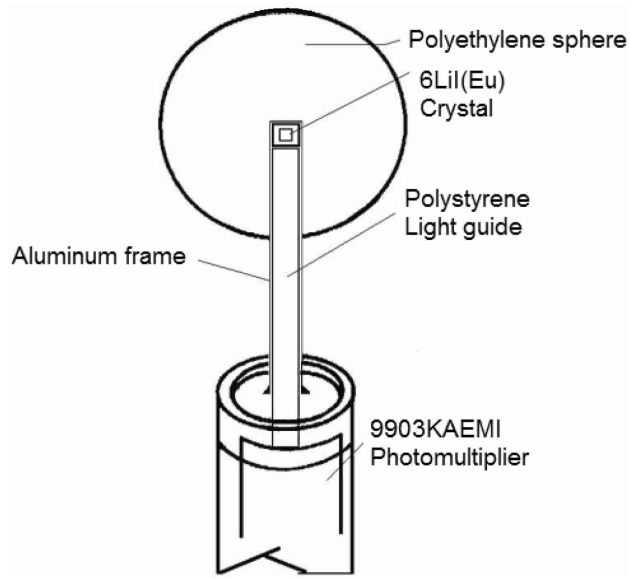

FIGURE 3. Schematic drawing of the neutron counter.

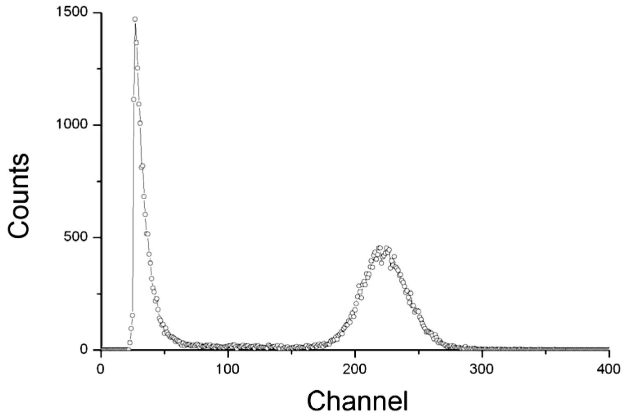

FIGURE 4. Typical pulse height spectrum for an Am-Be neutron source and 8 inch sphere.

Figure 3 shows a schematic drawing of the neutron counter, as constructed at ININ.

Figure 4 shows a typical pulse height spectrum obtained for an Am-Be neutron source. As it can be seen, it is possible to get a good separation between the gamma events and electronic noise from neutron events.

Each detector (sphere plus detector) has a peak response at a well defined energy value depending on the sphere size, but the overall response of the spectrometer drops sharply for neutron energies greater than 10 MeV, as can be seen in the energy response curve of Fig. 3 for the set of sphere sizes tested.

2. Experimental details

When neutrons of less than 20 MeV were the most energetic neutrons produced in those laboratories, this instrument worked well, considering, besides, that spheres with diameters of 15 and 18 inches were added [2,3,4], as can be seen

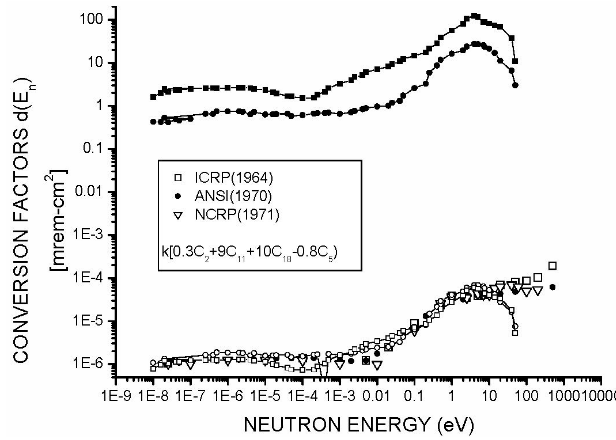

FIGURE 5. The calculated neutron dose equivalent using the Bonner spectrometer.

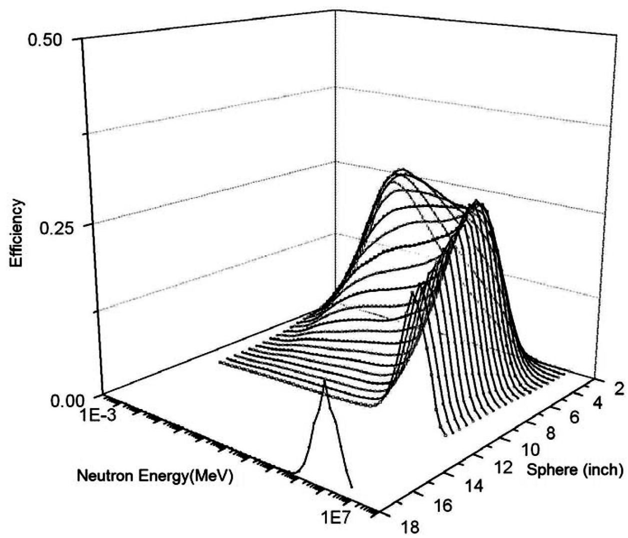

FIGURE 6. Calculated responses curves for 2, 3, 5, 8, 10, 12, 15 and 18 inches spheres.

in Fig. 6. In terms on the incident flux on each sphere,$\phi\left(E\right)$, and the spectrometer response, $R\left(r,E\right)$, the count rate $C\left(r\right)$obtained for each sphere due to a neutron field, is given by the Fredholm first kind equation [5]:

$$C\left(r\right)=\int_{Emin}^{Emax}R\left(r,E\right)\phi\left(E\right)dE \tag{1}$$

where: $C\left(r\right)$ is given in counts/s, $\phi\left(E\right)$ in neutrons/cm^{2}s eV, $R\left(r,E\right)$ in counts per cm^2/neutron y dE en eV.

Once $\phi\left(E\right)$ is known, the equivalent dose (DE) is calculated using the equation:

$$DE=\int_{Emin}^{Emax}d\left(E\right)Q\left(E\right)\phi\left(E\right)dE, \tag{2}$$

FIGURE 7. The new extended spheres at ININ.

Where, $d(E)$ are the conversion factors and $Q(E)$ are the quality factors.

Figure 5 shows as an example, the solution for Eq. (1) using the count rates of 2, 11, 18, and 5 inch polyethylene spheres, and the calculation of dose equivalent using Eq. (2). As can be seen, the fit of the Bonner spectrometer response to the dose equivalent curve [5] using the calibration factor k is rather good for the neutron energy range from thermal to 14 MeV.

However, with the construction of more energetic accelerators, more energetic neutrons (around 100 MeV) were produced, and, thus, a difficulty arose for the measurements of neutron spectra and the necessary dosimeter evaluations. Figure 6, shows the calculated response for the added Bonner sphere spectrometer, for neutrons from thermal to 100 MeV energies. The response functions were obtained by means of Monte Carlo calculations using an MCNP code [4].

As can be seen, the response functions of 15 and 18 inches Bonner spheres show peaks around 10 MeV and quickly decreases for energies a few MeV above, due to the decreasing of the n-p cross sections with increasing neutron energy. Moreover, the shape of the response curves in the high-energy region are very similar, with constant differences, which makes resolving spectral shapes for neutrons above E = 20 MeV more difficult. As a consequence, such systems are unreliable in environments with a large contribution of high energy neutrons. That is the case, if we are interested in the measurement of the neutron spectra and doses coming up from cosmic neutrons or around the new high energy accelerators.

In order to be able to study the neutron spectra for cases where the high-energy neutron component is important, it is desirable to extend the response of the Bonner sphere spectrometer to substantially higher energies. This requirement, unfortunately, is not solved by simply taking a larger polyethylene sphere as was discussed above.

Some laboratories have reported the design and construction of new spheres as complement to the conventional Bonner spectrometer. It is an interesting historical fact that T.W. Bonner and his group had the idea to extend the energy response of the spectrometer to higher neutron energies; on the basis that one extended sphere in use at our spectrometer had been designed and constructed by Bonner at Rice University, most probably during the early 60's.

So, in addition to the conventional spheres, our system is provided with two additional spheres in which lead, bismuth or copper shells are embedded in polyethylene, commonly called extended spheres.

With the new extended spheres we hope that the response function for the Bonner spectrometer at high neutron energies (>20 MeV) should be considerably raised, as can be seen in Ref. 6. The geometry parameters for the new extended spheres constructed consists of a 1.5 inches cupper, lead and bismuth hallow shells, 3.0 inches diameter embedded alternatively into two polyethylene spheres 6.0 and 10.0 inch outer radius, as is shown in Fig. 7.

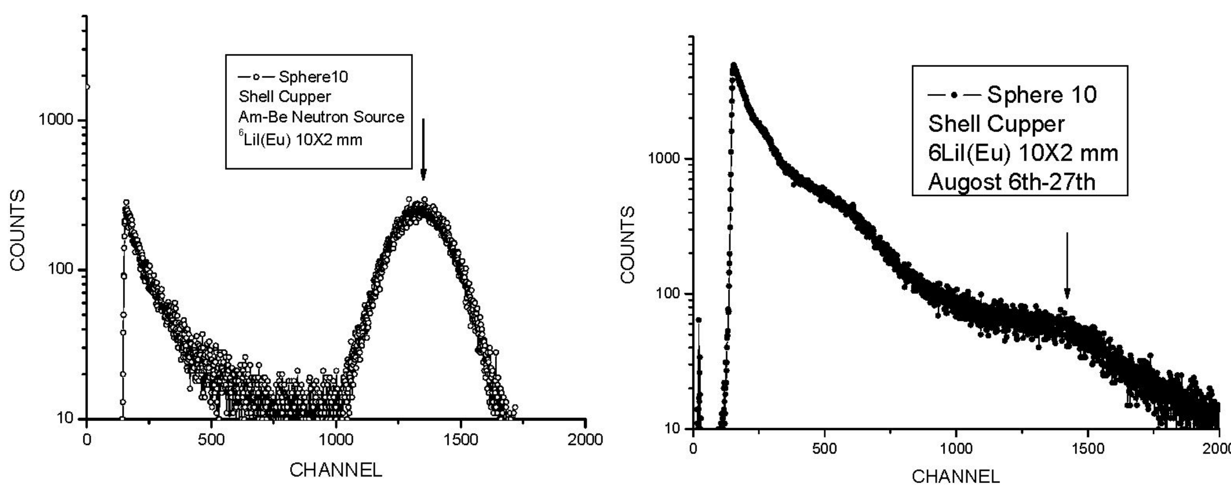

FIGURE 8. Pulse high spectra for an Am-Be neutron source (calibration) (left) and Cosmic neutrons (right).

3. Measurements

The measurement of the neutron spectrum at a height near 3000 meters above sea level asks for a monumental technical effort and requires a lot of time. Thinking in taking the data using a single crystal and alternatively every sphere, becomes a hard and maybe lost effort, due to the required time to gather the spectra, since as it has been reported [7] the energy spectrum of cosmic neutrons depends on actual climate parameters (like humidity and pressure).

A convenient method for measuring the spectrum is the collection of data using large number of spheres simultaneously. So, the spectrometer system designed by us will use seven different 10 mm diameter by 2 mm thick ^{6}LiI(Eu) crystals, coupled by adequate light pipes to 9903KA EMI photomultipliers. All the assembly (crystal, light pipe and phototube) are allocated inside aluminum frame which, besides adding mechanical support to the spheres, provide a black shadow for light pulse transmission.

Figure 8 illustrates a pulse height spectrum as recorded with an Am-Be source just before starting the recording of the outdoor data from cosmic neutrons, a spectrum of which is also depicted in this figure. As can be seen the cosmic neutrons are readily visible.

An important point to highlight, is the ability of the 6LiI(Eu) crystal to detect muons as noted by some authors [8]. In relation to the pulse height spectrum shown at the right, the peak near channel 600 corresponds, to a good approximation, to the energy deposited by 100 GeV muons on the 2 mm ^{6}LiI (Eu) crystal [9,10], taking into account that the energy associated with neutron peak is nearly the Q value (4.8 MeV) of the ^{6}Li(n,α)^{3}H reaction involved in the detection.

To protect the Bonner spheres and the detector electronics (high voltage for the photomultiplier basis, pre- and main amplifier) in outdoor measurements, a thermal plastic box cover 1 by 1 by 1 m was used. The cables transporting the signal and high voltages were isolated by plastic pipes to drive them indoors, where the acquisition system was allocated.

4. Conclusions

At the tandem laboratory of the National Institute of Nuclear Research, we have as was described above, a Bonner sphere spectrometer with polyethylene spheres with diameters from 2 to 18 inches. As we are interested in the measurement of the neutron spectra coming up from cosmic radiation, we intend to extend the response function of our spectrometer, for high energy neutrons.

Measuring the pulse height spectrum obtained for cosmic neutrons, as shown in Fig. 9, allowed us to choose the crystal ^{6}LiI(Eu) of 10 mm by 2 mm to construct a set of seven spheres which will be used simultaneously. This allows us to measure the neutron spectrum produced by cosmic radiation in México. The extended Bonner spectrometer so constructed, will be used in Mexico City, (2350 m high), the Nuclear Center of Mexico (2950m high) and in Sierra Negra, Veracruz, near 4000 m above sea level in a long term measurement programmer.

Acknowledgements

We are grateful to the machine shop of the Instituto de Física of the National University of Mexico (UNAM) and that of the Nuclear Centre of Mexico for its valuable contribution in the construction of the spectrometer.

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