Multiplicity Spectrum of NM64 Neutron Supermonitor and Hadron Energy Spectrum at Mountain Level

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Abstract

In comparison of the neutron multiplicity spectrum being observed at Tien-Shan NM64 type neutron supermonitor (690 g/cm^2) with the energy spectrum of cosmic ray hadrons which has been measured earlier a relation is drawn connecting the energy of an incident hadron with the value of neutron multiplicity (number of neutrons) being observed inside a monitor's unit: E=0.32M^2 GeV in the range above 3 GeV. Threshold energy for hadron registration with a neutron monitor lays in the range of 200 MeV.

1. Introduction

This work is to be considered as a continuation of our article [1]. The subject of investigation is the neutron multiplicity spectrum $R(M)$ being observed at the standard three-units neutron supermonitor of the NM64 type [5] at Tien-Shan level (690 g/cm^2). Under the neutron multiplicity M in our experiment is meant the total number of evaporation neutrons registered by the six SNM15 type neutron counters inside a neutron monitor unit. These neutrons are born as a result of nuclear disintegrations inside the monitor's lead absorber being caused by high-energy cascades from energetic cosmic ray hadrons.

The purpose of our work is to obtain a relation between the observed multiplicity M of a neutron event and the average energy of the incident hadron E_h on the basis of agreement of the observed neutron multiplicity spectrum $R(M)$ with the energy spectrum $F(E_h)$ of cosmic ray hadrons. The latter spectrum has been measured earlier at mountain level by the Aragats magnetic spectrometer [6] and Tien-Shan ionization calorimeter [2].

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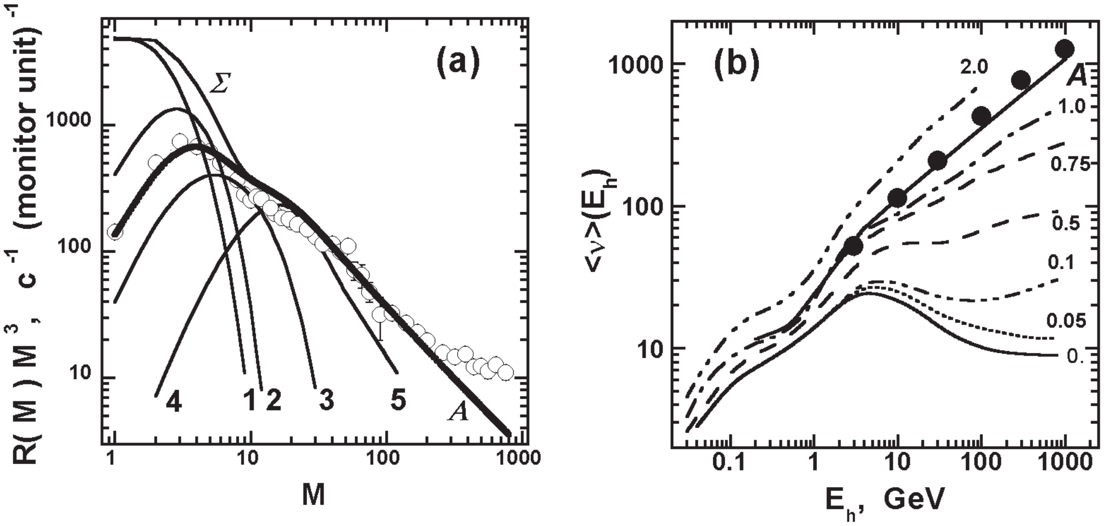

Fig. 1. Neutron multiplisity spectra (a): points — experiment, curves — calculations; Neutron production functions (b): curves with numbers — data from [5], curve *A* and the circles — results of the present calculation and SHIELD simulation.

2. Calculation procedure

The *R(M)* and *F(E_h)* spectra are connected with the well-known equation (see, for example, [5]):

$$R(M) = S\omega\eta \sum_{\nu=M}^{\infty} C_{\nu}^{M} \epsilon^{M} (1-\epsilon)^{\nu-M} \int\limits_{E_{thresh}}^{\infty} F(E_h) W(\nu, E_h) dE_h \qquad (1)$$

where $S\omega$ is the neutron monitor's unit acceptance angle, η — the interaction probability of cosmic ray hadrons inside the monitor's lead absorber, $\epsilon = 0.05$ — the registration efficiency of an evaporation neutron, ν — the multiplicity of evaporation neutrons and $W(\nu, E_h)$ — the probability distribution of the generation of ν neurons in interaction of a hadron having the energy E_h.

For our analysis the primary hadron spectrum at the level of 690 g/cm^2 was taken in the form: $F_h(E_h) = 32E_h^{-2.55} m^{-2} ster^{-1} GeV^{-1}$. This spectrum was obtained by the power-law fitting of the data of Aragats spectrometer in the energy range 2-10 GeV and the calorimeter data in the range above 300 GeV. Because the spectrometer was sensitive only to the primary protons, we have supposed that $F_h(E_h)=2F_p(E_p)$ and the pions deposit in the spectrum is negligible (in fact, less then 10%).

Fig.1a presents the multiplicity spectrum *R(M)* being observed at Tien-Shan neutron monitor. This spectrum has a complicated form in spite of the simple power shape of the energy spectrum of incident hadrons . In first turn, it is a consequence of a high energy threshold of nuclear disintegrations E_{thresh} which is of the order of some tens of MeV. If we suppose that the behavior of evaporation neutrons is the same as that of evaporation protons then, according to emulsion data [7], in the range until some GeV the mean neutron multiplicity $\overline{\nu}(E_h)$ must be increasing strongly and achieve some constant value $\overline{\nu}_0$. The finite depth of the monitor's lead absorber must result in cascade hadron multiplication at high primary energies and, as a consequence, in the growth of neutron production.

Fig.1b shows the results of calculation of the average neutron production for various values of the lead absorber thickness X_0 [5] (the numbers near the curves are the values of parameter $t = X_0/\lambda$, where $\lambda = 200 g/cm^2$ is the protons interaction length in lead). According to these data, the proper substitution in equation (1) for the case of an NM64 type supermonitor should be the $\overline{\nu}(E_h)$ dependence with $t = 0.75$. However, preliminary estimation has shown the necessity to use the $\overline{\nu}(E_h)$ curve with t=1. In our calculations we have used the following piece-power approximation of this curve:

$$\overline{\nu}_1(x)=x \text{ at } E_h=10\text{–}100 \text{ MeV}; \ \overline{\nu}_2(x)=6x^{0.22} \text{ at } E_h=100\text{–}400 \text{ MeV};$$
$$\overline{\nu}_3(x)=0.66x^{0.78} \text{ at } E_h=400\text{–}4000 \text{ MeV and } \overline{\nu}_4(x)=6.76x^{0.39} \text{ at } E_h > 4000 \text{ MeV}$$

(where $x = E_h/10$ MeV). Correspondingly, the energy integral in (1) was split to four parts: $I(\nu) = \int F(E_h)W(\nu, E_h)dE_h = I_1(\nu) + I_2(\nu) + I_3(\nu) + I_4(\nu)$ in accordance with the four approximation areas of $\overline{\nu}(E_h)$.

The values of neutron number ν were supposed to be distributed around the $\overline{\nu}$ according to an exponential low [3]: $W(\nu, E_h) = \frac{1}{\overline{\nu}(E_h)} exp(-\frac{\nu}{\overline{\nu}(E_h)})$

3. Discussion

The curve 5 on Fig.1 presents the result of our $R(M)$ spectrum's calculation with the above suppositions concerning the functions $\overline{\nu}(E_h)$ and $W(\nu, E_h)$ and the power primary pectrum. As it is seen, this curve agrees well with the absolute events intensity at M=30 but has a more steeper slope than the experimental spectrum. To achieve a better agreement between the calculation and experiment in the multiplicity range $M > 10$ it is necessary only to increase the power value in our $\overline{\nu}(E_h)$ approximation from 0.39 up to 0.5 for the energies above 4 GeV. The curve $\sum$ on Fig.1a presents the result for such a case. It is obvious, that the agreement between the $\sum$ curve and the experimental data in the range $M = 10-250$ is quite satisfactory both in intensity and in the slope. Nevertheless, in the range of low multiplicities, $M < 10$, our $\sum$ curve differs significantly from the experimental points. The discrepancy of this curve with the experiment in the range $M > 250$, which corresponds to the primary hadron energies E_h above 5 TeV, is caused by the influence of the group passages of the EAS core hadrons and can't be eliminated in the equation (1) based calculations.

To make it clear, which primary energies are accounting for the shape of $R(M)$ spectrum in various multiplicity ranges the partial spectra $R_1(M) - R_4(M)$ corresponding to the contributions of the integrals $I_1(\nu) - I_4(\nu)$ are shown on Fig.1a too. It may be seen, that the main deposit in the sum spectrum $R(M)$ in the range of $M > 20$ (where the $\sum$ curve agrees with experiment) gives the $R_4(M)$ spectrum which corresponds to the energies above 4 GeV. Therefore, one may think, that the $\overline{\nu}(E_h)$ dependence for these energies is finally determined: $\overline{\nu}(E_h) = 35E_h^{0.5}$ (where E_h is measured in GeV). For the 5% neutron registration efficiency ϵ the corresponding *neutron multiplicity dependence for the NM64 type supermonitor is* $\overline{M} = 1.75E_h^{0.5}$.

As for the $M < 10$ multiplicity range, to achieve the agreement between the calculated $R(M)$ spectrum and experimental points, it is necessary to set $R_1(M) = 0$ and to cut sufficiently the contribution of the $R_2(M)$ partial spectrum increasing the low integration limit: $x = 20$. The corresponding calculation result is shown by the A curves on Fig.1a and Fig.1b. This means that *the real threshold value for hadron registration by the NM64 type supermonitor is of the order of 200 MeV.*

To adjust the multiplicity spectra in the range $M < 10$ once and for all a more complicated procedure is necessary than that based on the equation (1) because the primary spectrum $F(E_h)$ isn't enough known in this range. In our further work we use the neutron transport code SHIELD [4]. Fig.1b presents the $\overline{\nu}(E_h)$ dependence calculated according to SHIELD code for the energies 1-1000 GeV (circles) together with our function $\overline{\nu}(E_h) = 35E_h^{0.5}$. It may be seen a good agreement between the SHIELD calculation and the curve A: deviation between them does not exceed 20% which is in a good accordance with our knowledge of the efficiency of evaporation neutrons registration ϵ.

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4. Referencies.

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