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Formation of Lead Mesoatoms in Neutron Monitor by Soft Negative Muons and Expected Atmospheric Electric Field Effect in Cosmic Ray Neutron Component

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Abstract

We extend our model of cosmic ray atmospheric electric field effect in the case of neutron monitor. We take into account that about 7 % of neutron monitor counting rate is caused by negative soft muons captured by lead nuclei and forming mesoatoms with neutron generation of a few MeV energy from lead. In this case neutron monitor works as an analyzer detecting muons of negative sign only. This is very important because atmospheric electric field acts in opposite way for positive and negative muons. On the basis of our general theory of cosmic ray meteorological effects, and by taking into account negative soft muon acceleration and deceleration in the Earth's atmosphere (in dependence of direction and intensity of electric field), we do a rough estimation on the possibility of detecting this effect in cosmic ray neutron component.

1 Introduction:

The atmospheric electric field effect in cosmic rays was discovered by Alexeenko et al. (1985, 1987) by using 4-minute data of cosmic ray muon component intensity measured with very high accuracy (the effective area of detector for muons with threshold energy 90 *MeV* was about 200 m^2 and for muons with threshold energy 20 *MeV* was about 6.9 m^2). The atmospheric electric field effect in muon component is mostly compensated because this effect for positive and negative particles has opposite sign. In principle we could observe a small effect because the flux of positive particles is a little bigger than that of negative particles (positive excess in secondary components of cosmic rays). The physical sense and general theory of this effect were discussed in Dorman (1987) and calculations of the expected effect were done in Dorman & Dorman (1995), by taking into account the muon positive excess in dependence of particle energy and the theory of muon component meteorological effects (Dorman 1957, 1972). In Dorman & Dorman (1995) it was shown that atmospheric electric field effect should exist in the neutron monitor intensity. This effect is caused by soft negative muons captured by lead nuclei, with formation of mesoatoms and further generation of additional neutrons. The relative number of these additional neutrons is different for different multiplicities and depends on cut-off rigidity, altitude and level of solar activity.

2 Formation of Lead Mesoatoms in Neutron Monitor by Soft Negative Muons in Dependence of Multiplicity and Altitude:

The atmospheric electric field effect is determined mostly by soft negative muons forming lead mesoatoms with following ejection of neutrons. Let us consider data on lead mesoatoms formation in neutron monitor in dependence of multiplicity and altitude. According to Nobles et al. (1967), the relative part of counting rate caused by formation of lead mesoatoms at sea level is 8.94% for multiplicity i=1, 6.7% for i=2 and 2.6% for i=3. At mountain altitude (about 3 km) the relative part of counting rate caused by formation of lead mesoatoms is smaller: 1.65% for multiplicity i=1, 0.68% for i=2 and only 0.3% for i=3. According to that, the biggest atmospheric electric field effect is expected at sea level for multiplicities i =1 and 2. At mountain altitude the atmospheric electric field effect is expected to be about 5 times smaller. These values were obtained for cut-off rigidities R_k≈4÷5 GV and low solar activity (near 1965).

3 Dependence of Lead Mesoatoms Formation on Cut-Off Rigidity and on Solar Activity Level:

The relative part of neutron monitor counting rate caused by formation of lead mesoatoms is proportional to muon component intensity and inverse proportional to nucleonic component intensity. Muon intensity decreases by about 10% from $R_k \le 2\,GV$ to $R_k \approx 15\,GV$, while neutron intensity decreases by about 50%. It means that the relative part of neutron monitor counting rate caused by formation of lead mesoatoms is expected to increase by about 40% from $R_k \le 2\,GV$ to $R_k \approx 15\,GV$. At sea level this will result in increasing multiplicity i =1 from 8.9% to 12.5%, i =2 from 6.7% to 9.4% and i =3 from 2.6% to 3.6%. From minimum to maximum solar activity, at $R_k \le 2\,GV$, the intensity of muon component decreases by about 6% and of neutron component by about 20%; it means that the relative part of neutron monitor counting rate caused by formation of lead mesoatoms is expected to increase by about 14% from minimum to maximum solar activity. Near equator this increase will be smaller.

4 Integral Multiplicity and General Theory of Atmospheric Electric Field Effect in Counting Rates of Neutron Multiplicities:

Let us consider the neutron monitor counting rate of multiplicity i at the point k. Let us call $\varepsilon_{\min}$ the minimum energy of detected secondary particles, R_k the cut-off rigidity, m_o the mass of air of the vertical column with unity cross-section over the detector, $D(R)$ the energy spectrum of primary cosmic rays, $T(h) = T_r(h)(1 + 0.378e(h)/h)$ the vertical distribution of absolute temperature over the detector (here $T_r(h)$ is the real absolute temperature and $e(h)$ the air humidity vertical distribution), and $E(h)$ the atmospheric electric field:

$$I_k^i(m_o, \varepsilon_{\min}, R_k, D(R), T(h), E(h)) = \int_{R_k}^{\infty} D(R) M_i(R, m_o, \varepsilon_{\min}, T(h), E(h)) dR \,. \quad (1)$$

M_i is the integral multiplicity (the neutron monitor counting rate of multiplicity i per square unit of detector caused by one primary particle with rigidity R). Let us consider the variation of M_i produced by the cosmic ray intensity change due to meteorological variations in the Earth's atmosphere:

$$\left(\frac{\Delta I_k^i}{I_{ko}^i} \right)_{mt} = \int_{R_k}^{\infty} \frac{\Delta M_i(R, m_o, \varepsilon_{\min}, T(h), E(h))}{M_{io}\left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}\right)} W_k^i\left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}\right) dR \,. \quad (2)$$

Here

$$W_k^i\left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}\right) = D_o(R) M_{io}\left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}\right) \big/ I_{ko}^i \quad (3)$$

is the coupling function introduced by Dorman (1957), and $\overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}$ are the average values and distributions characterizing the average meteorological condition at the observation point. In (2) and (3) I_{ko}^i is determined by (1) at $R_k = \overline{R_k}, m_o = \overline{m_o}$, $\varepsilon_{\min} = \overline{\varepsilon_{\min}}$, $T(h) = \overline{T(h)}$, $E(h) = \overline{E(h)}$. Equation (2) describes all meteorological effects by taking into account the dependence of meteorological coefficients on cut-off rigidity and cosmic ray primary spectrum (through changes in coupling function according to (3)).

Let us consider in more detail the equation (2), which can be rewritten in the form:

$$\left(\frac{\Delta I_k^i}{I_{ko}^i}\right)_{mt} = \left(\frac{\Delta I_k^i}{I_{ko}^i}\right)_m + \left(\frac{\Delta I_k^i}{I_{ko}^i}\right)_a + \left(\frac{\Delta I_k^i}{I_{ko}^i}\right)_t + \left(\frac{\Delta I_k^i}{I_{ko}^i}\right)_E, \quad (4)$$

where the first member in the right side describes the effect of atmospheric mass changes (barometric effect) due to changes in m_o, the second member describes the absorption effect due to changes in $\varepsilon_{\min}$, the third member describes the temperature effect due to changes in $T(h)$, and the fourth member describes the atmospheric electric field effect due to changes in $E(h)$. This last member can be evaluated by:

$$\left(\frac{\Delta I_k^i}{I_{ko}^i}\right)_E = \int_0^{m_o} \Delta E(h) dh \int_{R_k}^{\infty} \beta_E^i \left(h, R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right) W_k^i \left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}\right) dR, \quad (5)$$

where

$$\beta_E^i \left(h, R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right) = \frac{\delta M_i \left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right)}{\delta E(h) \times M_{io}\left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}\right)} \quad (6)$$

is the partial atmospheric electric field coefficient for multiplicity *i* and δ is the functional derivative.

The total atmospheric electric field coefficients α_E^i for multiplicity *i* can be computed from (5) by taking into account their dependence on R_k, $D(R)$ and on the average meteorological conditions:

$$\alpha_E^i \left(h, \overline{R_k}, \overline{D(R)}, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right) = \\ = \int_{R_k}^{\infty} \beta_E^i \left(h, R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right) W_k^i \left(R, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, \overline{E(h)}\right) dR, \quad (7)$$

so that, instead of (5) we obtain

$$\left(\frac{\Delta I_k^i}{I_{ko}^i}\right)_E = \int_0^{m_o} \Delta E(h) \alpha_E^i \left(h, \overline{R_k}, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right) dh, \quad (8)$$

where $\Delta E(h)$ is the vertical component of atmospheric electric field from the top of atmosphere to the level of observation m_o (mostly it is between the level m_o and level of clouds about 3-5 *km*).

5 Estimation of Total Atmospheric Electric Field Coefficients for Different Multiplicities in Dependence of Altitude, Cut-Off Rigidities and Level of Solar Activity:

Here we will use results of Dorman & Dorman (1995) on the expected atmospheric electric field effect for soft muons; the total atmospheric electric field coefficients for soft muons in the lower atmosphere can be approximated by

$$\alpha_E^{sm} \left(h, \overline{R_k}, \overline{D(R)}, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right) \approx 1.3 \times 10^{-3} (kV/m)^{-1} \left(g/cm^2\right)^{-1} \% . \quad (9)$$

By taking into account results of Section 2, we obtain for observations at sea level in the period of low solar activity at high and middle latitudes that

$$\alpha_E^{1,2,3} \left(h, \overline{R_k}, \overline{D(R)}, \overline{m_o}, \overline{\varepsilon_{\min}}, \overline{T(h)}, E(h)\right) \approx (11.6;\ 8.7;\ 3.4) \times 10^{-5} (kV/m)^{-1} \left(g/cm^2\right)^{-1} \% \quad (10)$$

correspondingly for multiplicities i =1, 2 and 3. For $E(h) \approx 20\, kV/m$ between $h = 1000\, g/cm^2$ and $h = 700\, g/cm^2$, it gives in neutron monitor counting rates changes by about 0.7%, 0.5% and 0.2% correspondingly in multiplicities i =1, 2 and 3.

With increasing solar activity the total atmospheric electric field coefficients will slightly increase, and at the maximum solar activity instead of (10) we obtain:

$$\alpha_E^{1,2,3}\left(h,\overline{R_k},\overline{D(R)},\overline{m_o},\overline{\varepsilon_{\min}},\overline{T(h)},E(h)\right)\approx(12.5;\ 9.4;\ 3.6)\times10^{-5}(kV/m)^{-1}\left(g/cm^2\right)^{-1}\%\,. \quad (11)$$

With increasing cut-off rigidity the total atmospheric electric field coefficients will be bigger; for example, in the period of low solar activity near equator the total atmospheric electric field coefficients will be:

$$\alpha_E^{1,2,3}\left(h,\overline{R_k},\overline{D(R)},\overline{m_o},\overline{\varepsilon_{\min}},\overline{T(h)},E(h)\right)\approx(16.2;\ 12.2;\ 4.7)\times10^{-5}(kV/m)^{-1}\left(g/cm^2\right)^{-1}\%\,. \quad (12)$$

With increasing the altitude of observations, the total atmospheric electric field coefficients decrease remarkably. For example, for observations at mountain altitude of about 3 *km* in the period of low solar activity, at high and middle latitudes:

$$\alpha_E^{1,2,3}\left(h,\overline{R_k},\overline{D(R)},\overline{m_o},\overline{\varepsilon_{\min}},\overline{T(h)},E(h)\right)\approx(2.1;\ 0.9;\ 0.4)\times10^{-5}(kV/m)^{-1}\left(g/cm^2\right)^{-1}\%\,.$$

6 Conclusions:

- The total atmospheric electric field coefficient decreases from $11.6\times10^{-5}(kV/m)^{-1}\left(g/cm^2\right)^{-1}\%$ to $8.7\times10^{-5}(kV/m)^{-1}\left(g/cm^2\right)^{-1}\%$ and then to $3.4\times10^{-5}(kV/m)^{-1}\left(g/cm^2\right)^{-1}\%$ with increasing neutron multiplicity from i=1 to i=2 and then to i=3.
- The total atmospheric electric field coefficient increases with increasing cut-off rigidity and with increasing solar activity.
- The total atmospheric electric field coefficient decreases with increasing the altitude of measurements.
- The typical atmospheric electric field effect at sea level (for $E(h)\approx 20\,kV/m$ between $h=1000\,g/cm^2$ and $h=700\,g/cm^2$) is expected to be about 0.7%, 0.5% and 0.2% correspondingly for multiplicities i =1, 2 and 3.
- Simultaneous measurements of atmospheric electric field effect in different neutron multiplicities at different latitudes and altitudes in periods of different solar activity levels could give the possibility to investigate this phenomenon in detail and to check the basic calculations given in this paper and in Dorman & Dorman (1995).

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