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Analytical Description of Solar Neutron Propagation in the Atmosphere for Different Initial Zenith Angles by Considering Scattering, Attenuation and Energy Change

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Abstract

We develop analytical calculation on solar neutron propagation in the atmosphere for different initial zenith angles, by taking into account not only scattering and attenuation, but also neutron energy change (leading to the increase of scattering angles, which is especially important for small energy solar neutrons). We test the commonly used conception that solar neutron propagation through the atmosphere for some initial zenith angle θ_0 of the Sun is the same as for vertical direction; only a different atmospheric depth ($h/\cos\theta_0$) should be considered. Our calculations of small angles multi-scattering of neutrons, by considering attenuation and energy change for different initial zenith angles, show that this suggestion is not correct. By taking into account the neutron energy change, we show that the asymmetry in solar neutron propagation and refraction effect increases with decreasing the solar neutron energy.

1 Introduction:

In Dorman et al (1997), Dorman & Valdez-Glacier (1997), Dorman et al. (1999) we extended the investigation of solar neutron propagation done by Shibata (1994) for vertical initial incidence, in the case of solar neutrons arriving at different initial zenith angles 0^0, 15^0, 30^0, 45^0, 60^0, 75^0. We did calculations of the angular distribution of arriving neutrons at different atmospheric levels by taking into account neutron scattering and attenuation. In a first approximation we supposed that the scattering angle in single interactions does not change during solar neutron propagation through the atmosphere. It means to neglect the energy change of neutrons and to obtain a lower limit of refraction effect. Here we will take into account the energy decrease of neutrons in scattering processes and the fact that each single effective scattering angle increases during solar neutron propagation through the atmosphere. We will show that the energy decrease of solar neutrons leads to increase the refraction effect.

2 Decrease of Solar Neutron Energy during Scattering in the Atmosphere:

In each elastic scattering with atoms of air (Oxygen or Nitrogen) the energy of neutrons E_n decreases, as an average, proportionally to the coefficient 0.8793. If a solar neutron arrives to the boundary of the atmosphere with initial energy E_{no} and initial zenith angle θ_o, the energy of neutron at a level h and at zenith angle θ will be

$$\ln\left(E_n\left(E_{no},\theta_o,\theta,h\right)\right)=\ln\left(E_o\right)+\left(L_e\left(\theta_o,\theta,h\right)/\lambda\right)\times\ln(0.8793), \quad (1)$$

where $L_e(\theta_o,\theta,h)$ (in g/cm^2) is the effective average path of neutrons propagating from the boundary of atmosphere (h=0) to the level h at zenith angle θ (determined in Doorman & Valdes-Galicia, 1997; Dorman et al., 1999), and λ is the average path for neutron scattering and attenuation. According to Shibata (1994) λ is about 110 g/cm^2 and is practically independent on energy of neutrons in a very broad interval.

3 Dependence of Single Effective Scattering Angle on Neutron Energy:

In Figure 1 it is shown the dependence of single effective scattering angle $\sigma(E_n)$ (in radiants) on $\ln(E_n)$ (where E_n is in *GeV*), based on data reviewed by Shibata (1994). This dependence can be approximated by a parabolic function:

$$\sigma(E_n) = 0.010337(\ln(E_n))^2 - 0.047038\ln(E_n) + 0.068585 \quad (2)$$

with correlation coefficient 0.99753.

Figure 1: The dependence of $\sigma(E_n)$ on $\ln(E_n)$ according to Shibata (1994) data

4 Expected Solar Neutron Angular Distribution in the Atmosphere:

Taking into account (1) and (2) we obtain, according to Dorman & Valdes-Galicia (1997), that the expected solar neutron angular distribution in the atmosphere at the depth *h* will be

$$f(E_{no}, \theta_o, \theta, h) = \left(\sqrt{2\pi}\sigma(E_n)\sqrt{L_e/\lambda}\right)^{-1} \exp\left(-\frac{(\theta - \theta_o)^2}{2\sigma(E_n)(L_e/\lambda)}\right) \exp(-L_e/\lambda), \quad (3)$$

where $E_n(E_{no}, \theta_o, \theta, h)$ and $\sigma(E_n)$ are determined respectively by (1) and (2), and $L_e(\theta_o, \theta, h)$ was determined by Dorman & Valdes-Galicia (1997). By numerical simulation of solar neutron propagation in the atmosphere for different initial zenith angles θ_0, Dorman et al. (1997) determined the solar neutron angular distributions at different levels *h* and Dorman & Valdes-Galicia (1997) compared these distributions with results obtained by the analytical approximation of type (3). It was found a good agreement in the case of constant neutron energy. Therefore, we think that eq. (3) could describe well the solar neutron angular distribution also when the change of neutron energy is included. We determined solar neutron angle distributions for $E_{no} = 0.1, 0.2, 0.3, 0.4, 0.5, 0.65, 0.8, 1.0, 1.2, 1.5, 2, 3, 5, 7, 10, 12,$ and $15\,GeV$, and for $\theta_0 = 0^0, 15^0, 30^0, 45^0, 60^0, 75^0$ at the levels *h* from 50 up to 1050 g/cm^2 in steps of 50 g/cm^2.

5 Solar Neutron Angular Distributions in the Atmosphere for Vertical Initial Approach:

As an example, we show in Figure 2 the angular distributions for $E_{no} = 0.1GeV$ and $\theta_o = 0^o$. The values on the ordinate axis show the expected flux per one initial neutron per unit of surface and per unit of time, and per 5 degrees of zenith angle.

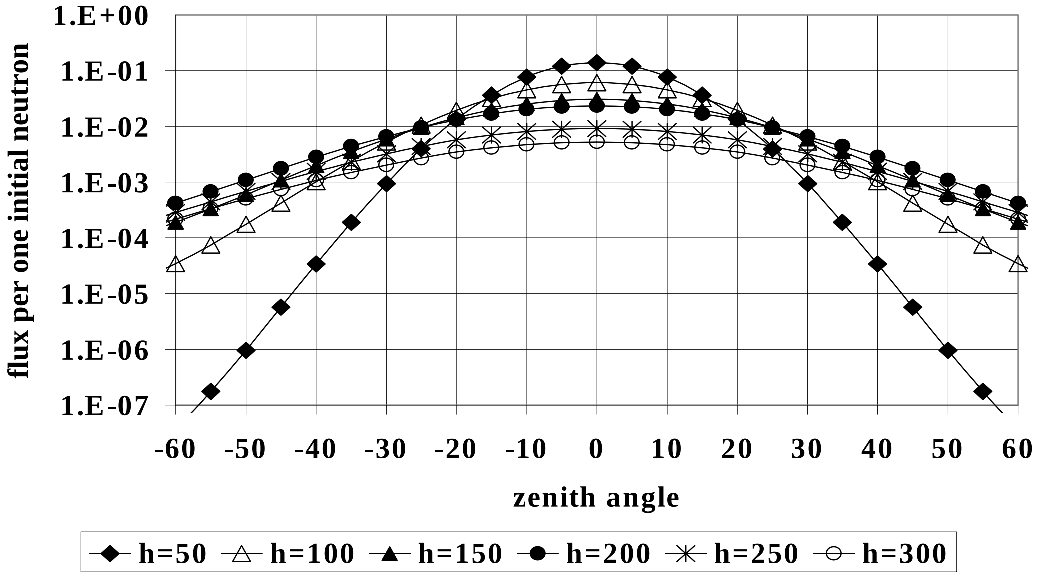

Figure 2: Expected angular distributions for $E_{no} = 0.1 GeV$ and $\theta_o = 0^o$ and different levels h

6 Distributions for Initial Zenith Angle 30^{o}:

The angular distributions are shown for this case in Figure 3 for $E_{no} = 1.0\ GeV$ and $\theta_o = 30^o$.

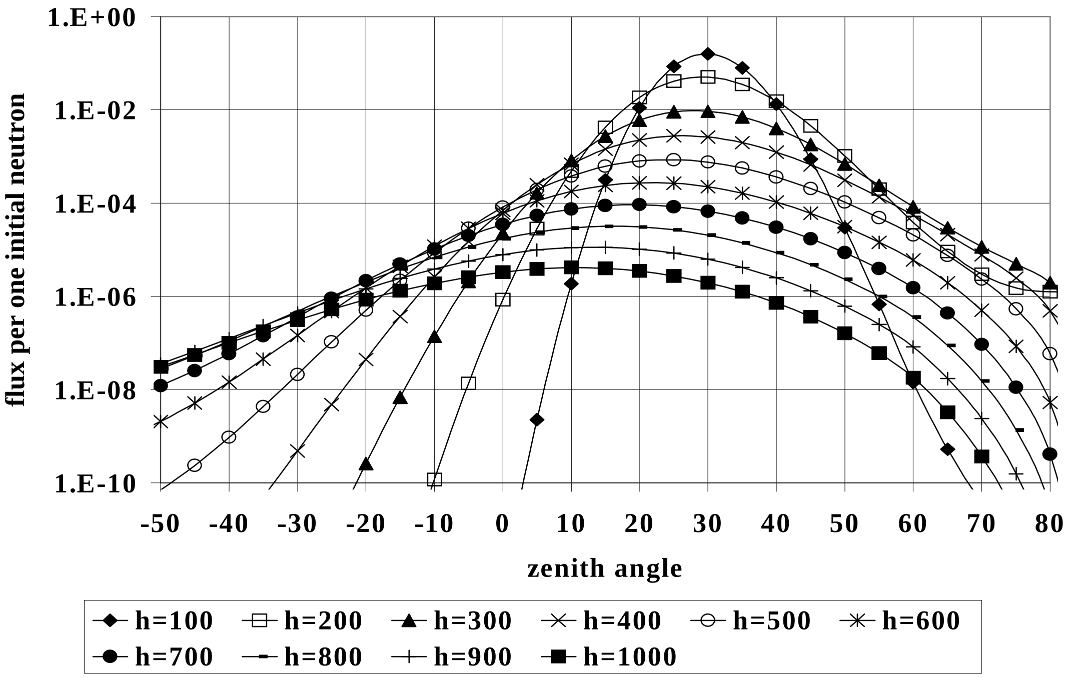

Figure 3: Expected angular distributions for $E_{no} = 1.0\ GeV$ and $\theta_o = 30^o$ and different levels h

7 Distributions for Initial Zenith Angle 75°:

The angular distributions are shown for this case in Figure 4 and 5 for initial energies 1 and 10 *GeV*.

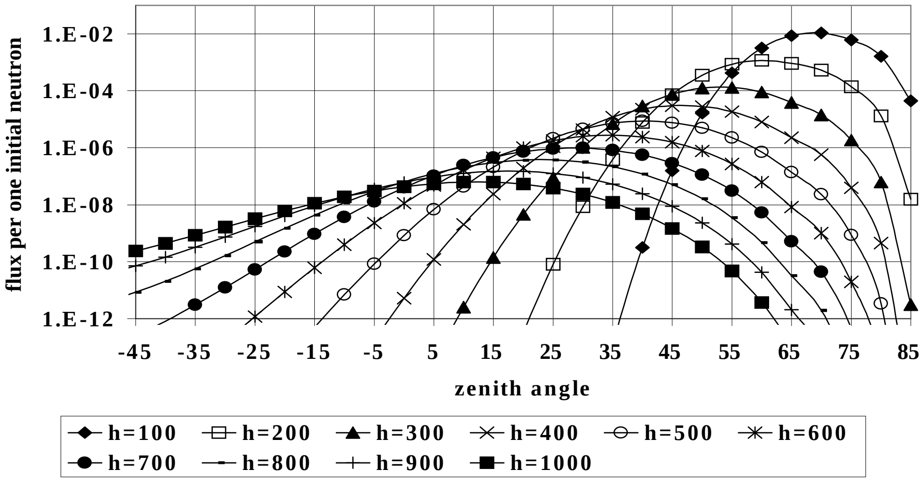

Figure 4: Expected angular distributions for $E_{no} = 1.0\ GeV$ and $\theta_o = 75^o$ and different levels *h*

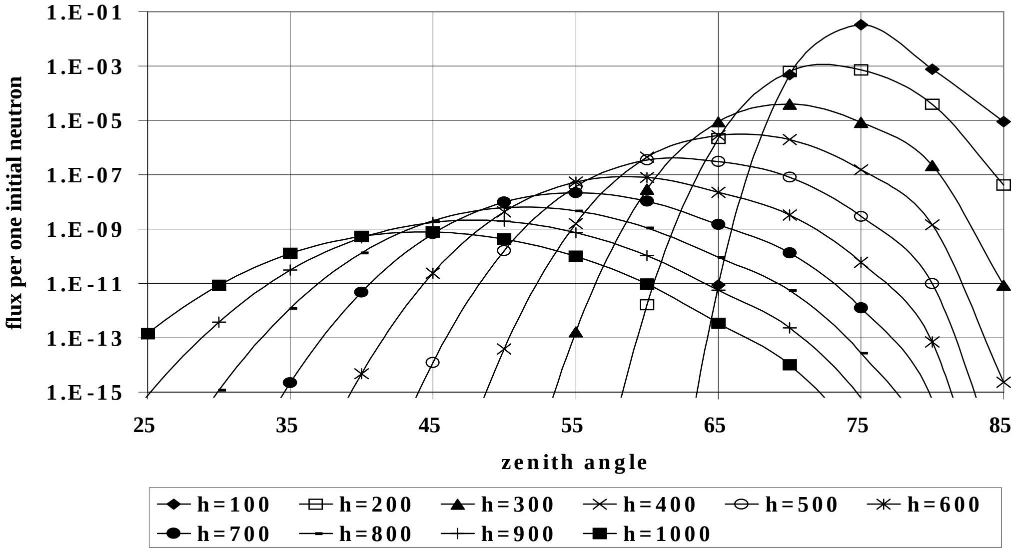

Figure 5: Expected angular distributions for $E_{no} = 10\ GeV$ and $\theta_o = 75^o$ and different levels *h*

8 Conclusions:

The comparison of present results with those of Dorman et al. (1977, 1999) shows that, by including the change of neutron energy in our previous model, the displacement of angular distributions to vertical direction with increasing *h* and with increasing θ_0 (refraction effect) becomes bigger and more evident.

References

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