Proceedings of ICRC 2001: 3077 © Copernicus Gesellschaft 2001

ICRC 2001

Monte Carlo simulations using some nuclear interaction models on solar neutron propagation in the atmosphere

K. Yusaku and S. Makio

Department of Physics, Faculty of Engineering, Yokohama National University. 79-5 Tokiwadai, Hodogaya-ku, Yokohama, 240-8501, Japan

Abstract. Tibet ASγ group constructed a new type of solar neutron telescope at Yangbajing (606 g/cm^2) in 1998. Monte Carlo simulations on the propagation of solar neutrons through the Earth's atmosphere has been done in order to evaluate the performance of the detector for solar neutrons. Two kinds of the nuclear cascade models were used in Monte Carlo calculations. One is the intranuclear cascade evaporation model by using CALOR89 and another is nuclear cascade model developed by STE Laboratory in Nagoya university group. The attenuation of neutrons in the atmosphere at the observational site were estimated using two simulation code. The survival ratio of neutron calculated by CALOR 89 is approximately two times larger than Nagoya-model above 200 MeV. The detection efficiency for solar neutron was also estimated by CALOR89 as 25 $\sim$ 40 % in the energy region from 100 MeV to 1500 MeV. Finally the sensitivity of Tibet neutron telescope for the neutron produced by solar flare was studied by using CALOR89. We found that Tibet neutron telescope has the good performance of getting solar neutrons with high significance of more than 50 σ for the flare with neutron emissivity spectrum; $\frac{\mathrm{dI}}{\mathrm{dE}} = 1.0 \times 10^{27} \times (\frac{\mathrm{E}}{100})^{-4}[\mathrm{MeV}^{-1}\mathrm{sr}^{-1}\mathrm{s}^{-1}]$.

1 Introduction

The understanding of particle acceleration mechanisms is a fundermental subject in astrophysics. Although various kind of experiments have been so far done to study this subject, the acceleration processes for high energy cosmic rays are not established definitely. The Sun is the nearest site capable of accelerating particles up to high energy. When the Sun becomes active, flares are frequently observed on its surface. Solar flares are the most energetic events occurring on the Sun and they provide us with a unique opportunity for studying the acceleration of charged particles. The acceleration process can be studied from various emissions of X-rays and γ-rays as well as observations in the radio waveband in which certain phenomena have the clear characteristics of the emission of high energy electrons. Furthermore, some of the most powerful flares are strong source of high energy protons and ions which will be detected soon after the flare as solar cosmic rays at the Earth. Among solar cosmic rays, high energy neutrons come straight from the flare position to the Earth without the modulation of the magnetic fields between the Sun and the Earth and provide direct information about the acceleration mechanism of charged particles. High energy neutrons which are observed in the vicinity of the Earth can be created in spallation interactions of high energy proton or helium nuclei with the ambient gas, and these must be created at the same time as the high energy electrons responsible for the hard X-ray and γ-ray emission. Thus, simultaneous observation of neutrons with radio waves, X-rays and γ-rays is crucial to understand where and how solar cosmic rays are accelerated when flares happen at the surface of the Sun.

Correspondence to: K. Yusaku (katayose@ynu.ac.jp)

In order to detect high energy solar neutrons, Tibet ASγ group constructed a new type of solar neutron telescope at Yangbajing, Tibet (4300m) in 1998. Monte Carlo simulations on the propagation of solar neutron through the Earth's atmosphere has been done in order to estimate the performance of the detector for solar neutrons. After entering the atmosphere of the Earth, solar neutrons are scattered or absorbed by air nuclei. One must fully understand these effects in order to be able to deduce information on the intensity of neutrons at the top of the atmosphere from data obtained at observation sites. Until now, some calculations of the propagation of solar neutrons in the atmosphere have be done. One is the calculation by Debrunner et al.[H. Debrunner (1968)] on solar neutron sensitivity using neutron monitors and another calculation was by Nagoya university group[S. Shibata (1994)]. There exists, however, a little differences between the sensitivity of neutron monitors calculated by two simulators[H. Debrunner (1997)][S. Shibata (1994)]. Two different simulation code were applied for the calculation of the propagation of solar neutron through the Earth's atmosphere and the results were compared in this analysis . One is

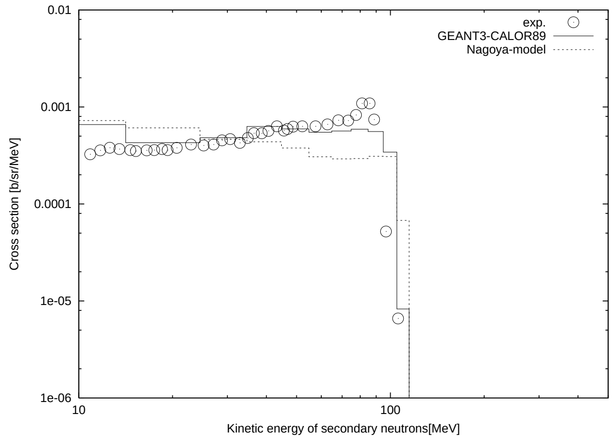

Fig. 1. Double differential cross sections.
Proton(113MeV)+Carbon→Neutron(7.5deg.)

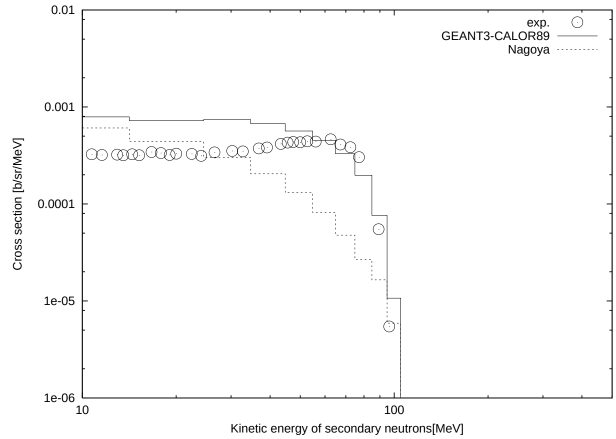

Fig. 2. Double differential cross sections.
Proton(113MeV)+Carbon→Neutron(30deg.).

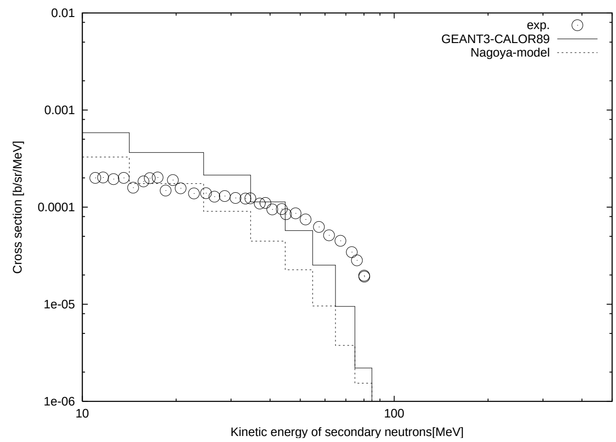

Fig. 3. Double differential cross sections.
Proton(113MeV)+Carbon→Neutron(60deg.).

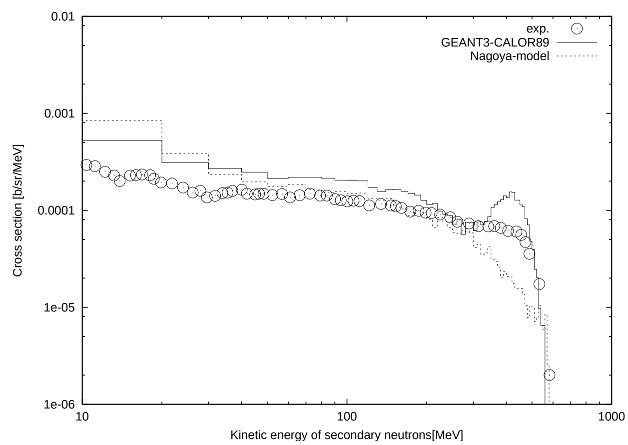

Fig. 4. Double differential cross sections.
Proton(597MeV)+Carbon→Neutron(30deg.).

Monte Carlo code GEANT3 with CALOR89 and another is Nagoya-model. The Monte Calro package GEANT[R.Brun (1993)] is the most widely used program to study large scale detectors and CALOR89 program package [H. W. Bertini (1963)][H. W. Bertini (1969)] simulates hadronic interactions down to 1 MeV for nucleons and charged pions and into thermal region for neutrons. Especially in this simulation the interactions with energy range from several tens MeV to several GeV are important. In CALOR89 within this energy range, calculation of interactions of nucleons is based on the intranuclear-cascade-evaporation-model as implemented by Bertini. Another is the Monte Calro code developed in Nagoya university group. S.Shibata[S. Shibata (1994)] calculated the transport of solar neutrons through the atmosphere of the Earth by a Monte Calro method using a nuclear interaction model in which cross sections for nucleon bombardment of Air nuclei are extrapolated from those for nucleon and Carbon. The elastic scattering of a neutron with an air nucleus is significant in this code . We also made the same simulator based on this model and simulated the propagation of neutrons through the atmosphere.

2 Double Differential Neutron production Cross Sections

The interactions with energy range from several tens MeV to a few GeV are important in our simulation. Differential(p, xn) cross sections for 113 MeV protons and 597 MeV protons were calculated by both simulation codes. Those results were compared with experiments [M. M. Meier (1989)],[W. B. Amain (1993)]. Figure 1, 2, 3 show differential(p, xn) cross sections at emission angles of 7.5, 30, and 60 degree for the 113 MeV protons bombardment of Carbon target with thickness of 9.43 g/cm^2. Open circles show experiment and solid histgram and dashed histgram show the results by CALOR89 and Nagoya-model respectively. Reasonably good agreement between calculations and experiment is obtained in the energy region from 10 MeV to about 40 MeV within factor of 2 ∼3. But near the incident energy, the cross sections calculated by Nagoya-model are smaller than

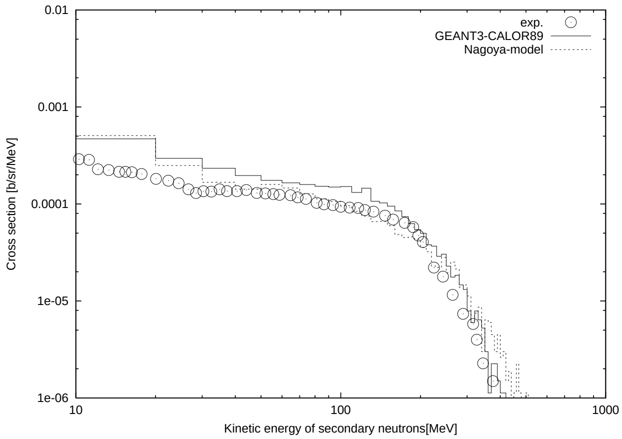

Fig. 5. Double differential cross sections. Proton(597MeV)+Carbon→Neutron(60deg.).

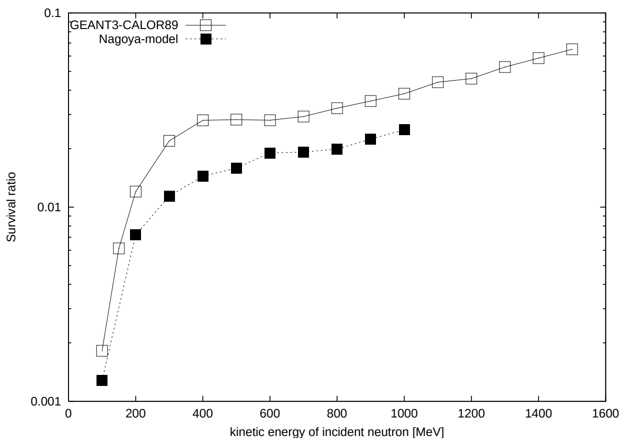

Fig. 6. Survival ratio of solar neutron at Yangbajing level. Zenith angle of incident direction is 6 degrees.

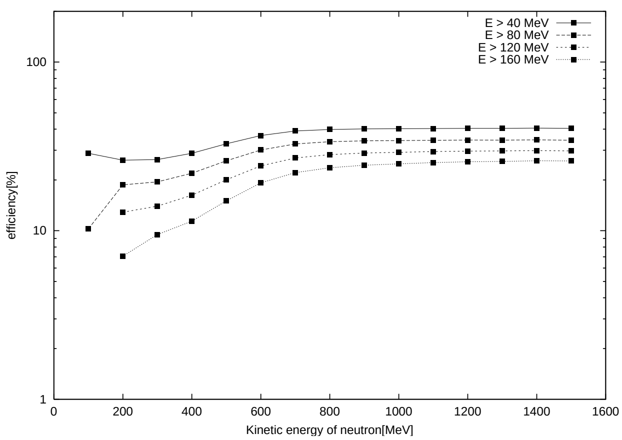

Fig. 7. Detection efficiency of Tibet neutron telescope calculated by CALOR89 .

CALOR89. The difference is remarkable at the emission angles 7.5 and 30 degrees especially. Figure 4 and 5 show dif-

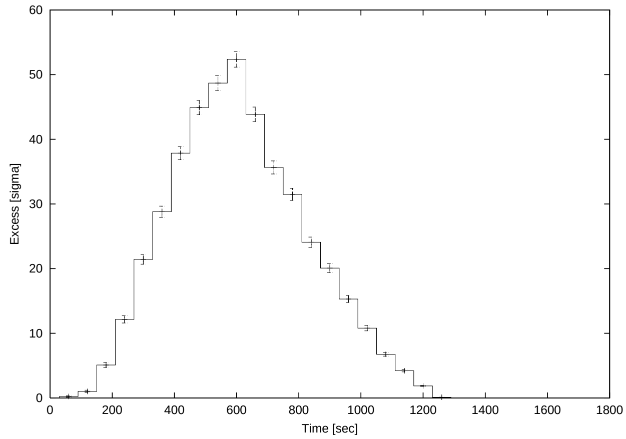

Fig. 8. Time variation of expected excess.

ferential(p, xn) cross sections at emission angles of 30 and 60 degree, respectively, for the 597 MeV protons bombardment of Carbon target with thickness of 0.56 g/cm^2. CALOR89 is larger than experiment near the incident energy at the emission angle 30 degrees while Nagoya-model is smaller than experiment. It seems that the cross section of CALOR89 is larger than Nagoya-model in the higher energy region. From these results, we can expect that the neutron attenuation calculated by CALOR89 is smaller than that of Nagoya-model.

3 The attenuation of neutrons in the atmosphere of the Earth

The propagation of solar neutrons through the atmosphere of the Earth has been calculated by Monte Calro method using GEANT3-CALOR89 and Nagoya-model. The incident neutron and all produced nucleons are followed until their kinetic energies drop below a given threshold level 40 MeV or until they arrive at Yangbajing level. The particle species, energies and angles of each nucleon at Yangbajing level is recorded. The survival ratio of the neutrons at the Yangbajing level are shown as a function of incident energies at top of the atmosphere in Figure 6. Solid line shows the result of CALOR89 and dashed line shows that of Nagoya-model respectively. The survival ratio calculated by CALOR89 is approximately 0.18 % at 100 MeV. It increases with incident energy rapidly and then its slope become gently around 400 MeV. The behavior of survival ratio is similar for both simulators. Although their absolute value is different. The difference between CALOR89 and Nagoya-model become largest around 400 MeV. CALOR
89's ratio is approximately 2.8 % at 400 MeV. It is 1.9 times higher than the result by Nagoya-model.

4 Sensitivity of Neutron telescope to solar neutrons

The sensitivity of Tibet neutron telescope to solar neutron was estimated by using CALOR89.

4.1 Tibet neutron telescope

Neutron telescope was constructed at Yangbajing (4300 m, 90 °.53 E and 30 °.11 N) in Tibet in 1998 October [Katayose Y. (1997)]. The atmospheric depth at Yangbajing corresponds to 606 g/cm^2. The telescope consists of 9 scintillation counters of 1 m^2 each and proportional counters. The scintillators of 1 m^2 each and 40 cm thickness are arranged as a 3×3 square. Each scintillator equipped with a phototube (HPK R1512) detects the recoil protons converted by incident neutrons in the scintillator. Each proportional counter is a cylinder with 10 cmϕ and 3.3 m length containing PR gas(Ar;90 %, CH_4; 10%, gas pressure; 0.8 atm). The top and four sides of the scintillator array are covered by the proportional counters (anti-counters) which work to veto charged particles. Below the scintillator array, the four layers of proportional counters are placed to detect high energy neutrons which penetrate the scintillators. The number of proportional counters in each layer is 30. These counters in each layer are aligned lengthwise at right angles with those in adjacent layers with an covering area of 3 m $\times$ 3 m. There are two sets of X and Y layer which can be used to determine the direction of recoil protons. Furthermore, two layers of wooden absorber with thickness 10 cm and density 0.8 g/cm^3 are put between the layers of proportional counters.

4.2 Detection efficiency

The detection efficiencies of telescope for neutrons are investigated by using CALOR89. Figure 7 shows the detection efficiency of each channel for the incident neutrons with the direction angle of $\theta = 6$ degrees. The lines show the efficiency of the different threshold energies, $>$ 40 MeV, $>$ 80 MeV, $>$ 120 MeV, $>$ 160 MeV respectively. The efficiencies expected lowest energy is $\sim$ 28 % at 100 MeV and $\sim$ 40 % at 400 MeV.

4.3 Time profile

The sensitivity of detector for the neutrons produced by solar flare was studied by the simulation of propagation both in the atmosphere and detector using CALOR89. Lower energy particles are detected by scintillators, the average counting rate for neutral particles at the discrimination level with 40 MeV is measured to be about 8.9×10^3 m$^{-2}\cdot$ min^{-1} ($>$ 40 MeV), [Katayose Y. (1997)]. It is assumed that the flux of neutrons emitted from the Sun is given by next equation,

$$\frac{\mathrm{dI}}{\mathrm{dE}} = 1.0 \times 10^{27} \times \left(\frac{\mathrm{E}}{100}\right)^{-4} [\mathrm{MeV}^{-1}\mathrm{sr}^{-1}\mathrm{s}^{-1}], (\mathrm{E} > 100)$$

where E is kinetic energy of neutron in MeV. In addition, it was supposed that the flare started in the median at Yangbajing with altitude of 84 degrees and the energetic neutrons were emitted during 10 seconds. Finally significances were estimated by using experimental count rate and simulated events as, $\sigma = \frac{N_{sim}}{\sqrt{N_{bg}}}$,where N_{sim} is event rate obtained by simulation and N_{bg} is background count rate. Figure 8 shows time variation of expected excess for the count rate in 30 seconds. The significances in lowest energy channel of $>$ 40 MeV is expected to be more than 50 σ.

5 Conclusion

In order to evaluate performance of the detector for solar neutrons, Monte Carlo simulations on the propagation of solar neutron through the Earth's atmosphere has been done by using CALOR89 and the simulator based on Nagoya-model. The survival ratio of neutron calculated by CALOR89 is approximately two times larger than Nagoya-model above 200 MeV. The detection efficiency of solar neutron was estimated by CALOR89 as 25 % $\sim$ 40 % in the energy range from 100 MeV to 1500 MeV. We found that Tibet neutron telescope can get neutron from solar flare with large significance of 50 σ in the time profile.

References

R.Brun, F.Carminati, 1993, *GEANT Detector Description and Simulation Tool*, CERN Program Library Long Writeup W5013.

H. Debrunner et al., Can. J. Phys., vol. 46, S1069, 1968.

H. Debrunner et al., Apj., vol. 479, 997, 1997.

H. W. Bertini, ORNL-3383, OakRidge National Laboratory, 1963.

H. W. Bertini, Phys. Rev. vol. 188, 1711, 1969.

Katayose Y. et al., Proc. 26th ICRC(Utah), SH. 1. 3. 07, vol 6, p58-62, 1999.

M. M. Meier et al., Nucl. Sci. Eng. vol. 102, 310, 1989.

S. Shibata., J. Geophys. Res., vol 99, 6651, 1994.

W. B. Amain et al., Nucl. Sci. Eng. vol. 115, 1, 1993.