Proceedings of ICRC 2001: 3065 © Copernicus Gesellschaft 2001

ICRC 2001

GEANT4 Monte Carlo simulation of the SONTRAC detector

L. Desorgher[1], E. O. Flückiger[1], R. S. Miller[2], J. M. Ryan[2], J. R. Macri[2], and M. L. McConnell[2]

[1]Physikalisches Institut, Universität Bern, Sidlerstrasse 5, CH-3012 Bern
[2]Space Science Center, University of New Hampshire, Durham, NH 03824

Abstract. We have done Monte Carlo simulations of the SONTRAC detector with the GEANT4 toolkit. We present results of proton range and neutron detection calculations.

1 Introduction

The Solar Neutron Tracking (SONTRAC) detector is designed to measure neutrons in the energy range 20-250 MeV (Ryan et al., 1999; Wunderer, 1997). The detecting part of SONTRAC consists of a block of scintillating fibers stacked in orthogonal layers and viewed by image intensified CCD cameras. Neutrons are detected through single and double neutron-proton (np) elastic scattering in the scintillating fiber block. The energy and direction of an incident neutron can be determined from stereoscopic images of the scintillation tracks of the recoil protons.

A scientific model of SONTRAC with a $5 \times 5 \times 5 cm^3$ scintillating fiber block has been developed at the Space Science Center of the University of New Hampshire (Miller, R. S., 2001). It has been irradiated with the proton and neutron beam facility at the Crocker Nuclear Laboratory, UC Davis (Miller, R. S., 2001; Romero et al., 1980; Jungerman, J. A. and Brady, F. P. , 1970). We have developed a SONTRAC Monte Carlo GEANT4 application (GEANT4, 2001). In this application the scintillating fiber block is modeled by a polystyrene block with the same density and composition as in the SONTRAC scientific model. In section 2 of this paper, the GEANT4 computed range of a proton crossing the SONTRAC scintillating block is presented in dependence of energy and compared to measurements. In section 3, GEANT4 simulation results of the neutron detection by SONTRAC in the single and double elastic np scattering mode are discussed. Conclusions are presented in section 4.

Correspondence to: L. Desorgher
(desorgher@phim.unibe.ch)

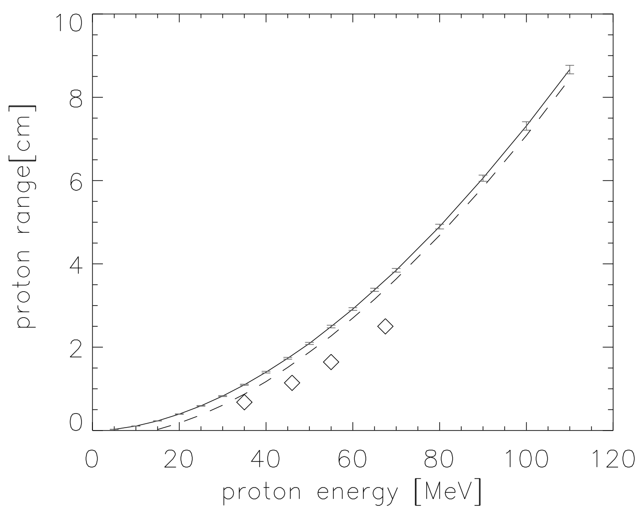

Fig. 1. GEANT4 computed proton range of a scintillating material with the same density and composition as the SONTRAC scintillating fibers (solid lines). The dashed line is obtained when the proton beam crosses first an aluminum layer of $1mm$. The diamonds represent measurements with the SONTRAC scientific model.

2 Proton range

The stereoscopic imaging system in SONTRAC permits to reconstruct 3D recoil proton tracks in the scintillating block. From the track length of a proton we can deduce its energy provided that the proton range vs energy curve is known. We have computed this range vs energy information with our GEANT4 SONTRAC code. For 18 different energies $\leq 110MeV$ we have computed the range of 10000 incoming monoenergetic protons. In Figure 1 the solid line represents the mean proton range versus energy. The error bars represent the statistical dispersion at 1σ. The diamonds represent SONTRAC scientific model proton range measurements at four different energies. The measured ranges are significantly lower than the computations.

In the SONTRAC scientific model a $1mm$ thick aluminum

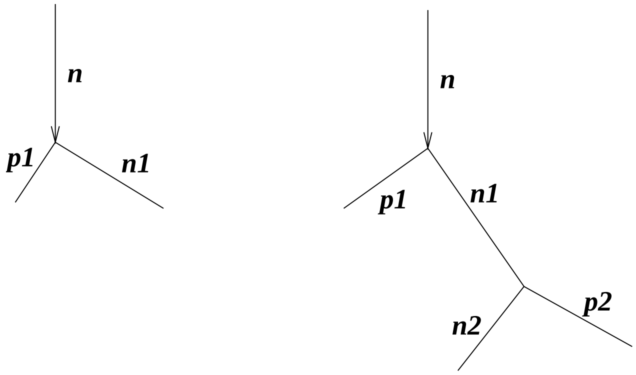

Fig. 2. Illustration of single (left) and double (right) np elastic scattering in the SONTRAC scintillating block.

layer covers the side through which the proton or neutron beam penetrates the detector. Proton energy loss in this Al plate leads to a decrease in the scintillating proton range. The dashed line in Figure 1 represents the proton range calculated by considering this Al layer in the GEANT4 simulations.

At the Crocker Nuclear Laboratory, the proton beam intensity is significantly reduced by the use of a $6\mu m$ thick tantalum target (Romero et al., 1980; Jungerman, J. A. and Brady, F. P. , 1970). By interacting with this Ta target some protons of the initial beam capture electrons and become neutral hydrogen atoms. The other protons are deviated out of the beam by a magnetic field. At the end of the vacuum chamber the neutral hydrogen atoms are stripped of their electrons in a thin kapton foil. With this procedure, a proton beam with lower intensity but practically the same energy as the beam hitting the Ta target is obtained. For estimating the energy difference between the proton beam before and after its reduction, we have added to our Monte Carlo code the ionization energy loss of protons in the Ta target and the kapton foil. We have not modeled the exact electron capture and stripping process. The range reduction resulting from this energy loss is negligible.

For limiting the fiber crosstalk by scintillation photons, the polystyrene core of each scintillating fiber used in the SONTRAC scientific model is covered by two cladding layers and an extra mural absorbing painting. These additional materials are more dense than the fiber polystyrene core and are therefore the source of a reduction of the proton range in the scintillating block. We received information on their composition from the manufacturer when writing this paper. The influence of these additional materials on the proton range will be modeled in future simulations.

3 Neutron detection

Neutron interaction mechanisms used in the SONTRAC detection concept are illustrated in Figure 2. In the single np elastic scattering mode, an incident neutron scatters elastically only once on a hydrogen nucleus of the polystyrene

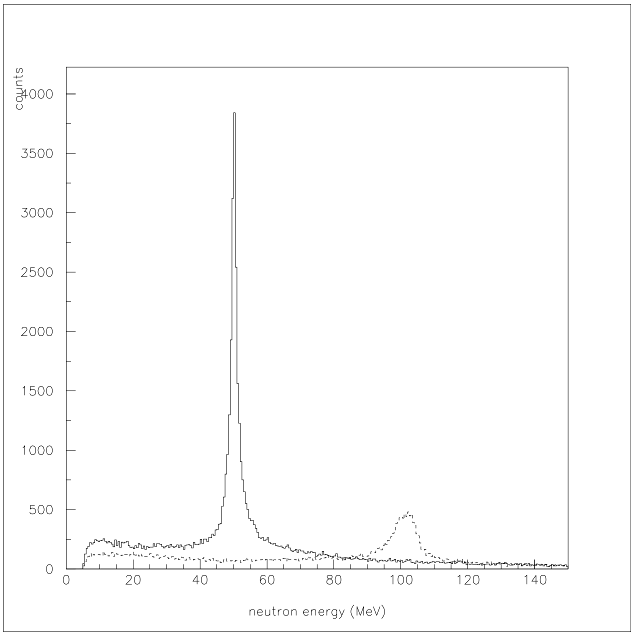

Fig. 3. GEANT4 simulated detection of 50 MeV (solid line), and 100 MeV (dashed line) neutrons by a $10 \times 10 \times 10 cm^3$ SONTRAC in the single np elastic scattering mode. For each energy 500000 events were processed.

block. The resulting recoil proton $p1$ is then tracked by SONTRAC. In the double np elastic scattering mode the neutron scatters a second time, and two recoil proton ($p1$ and $p2$) tracks are registered by SONTRAC. By elastic scattering on a carbon nucleus of a scintillating fiber, a neutron is slightly deviated but no scintillating tracks are observed. We have implemented the physics of np and nC elastic scattering in the SONTRAC GEANT4 code. Total and differential cross sections of these mechanisms have been taken from the Evaluated Nuclear Data File library (ENDF, 2001).

Incident neutrons can also interact inelastically with carbon nuclei in the scintillating fibers. For modeling this nC inelastic scattering we have used the GHEISHA model available in GEANT4 (GEANT4, 2001; Fesefeldt, H., 1985).

We have simulated the interaction of 50 and $100 MeV$ neutrons at normal incidence with a $10 \times 10 \times 10 cm^3$ scintillating block. For each energy we have processed 500000 neutrons. For each crossing of a neutron through the scintillating block, we registered the tracks of any charged particles with a range greater than the scintillating fibers section. Events with single and double tracks were considered as recoil proton signature from single and double np elastic scattering respectively. Other events were rejected. From the track length, we computed the corresponding proton energy by interpolation of the range vs energy curve in Figure 1. Finally from each track information we deduced the energy, momentum, and start position of recoil protons. The procedure to compute the incident neutron energy and direction form recoil proton track is described in subsections 3.1 and 3.2.

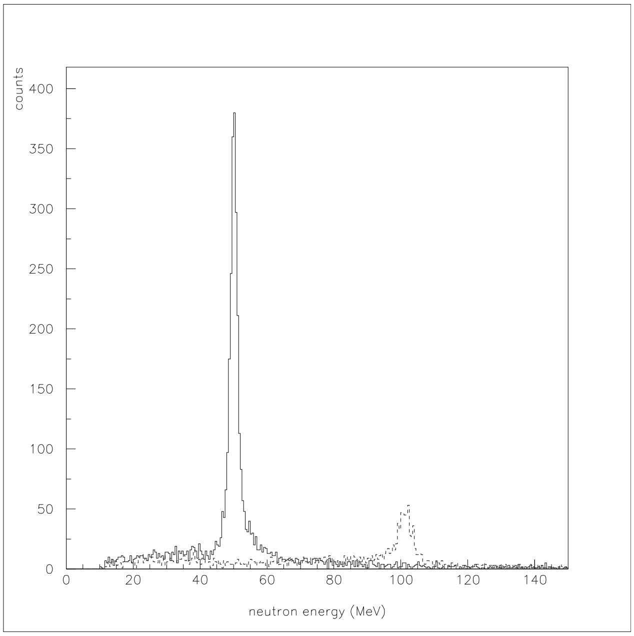

Fig. 4. GEANT4 simulated detection of 50 MeV(solid line), and 100 MeV (dashed line) neutrons by a $10 \times 10 \times 10cm^3$ SONTRAC in the double np elastic scattering mode. For each energy 500000 events were processed.

3.1 Single np elastic scattering detection mode

When its direction is known, the energy of an incident neutron can be deduced from the energy and momentum of a single recoil proton. By considering the energy and momentum conservation in the np elastic scattering process we obtain for the kinetic energy of an incident neutron

$$T_n = \frac{-b - \rho}{2a} \tag{1}$$

where

$$\begin{aligned} a &= (T_p^2 - p_{p\parallel}^2) \\ b &= 2m_p T_p^2 \\ \rho &= \sqrt{b^2 - 4ac} \end{aligned} \tag{2}$$

with

$$c = T_p 2m_p^2 + p_{p\parallel}^2 m_n^2 \tag{3}$$

and m_n the neutron rest energy, T_p the recoil proton kinetic energy, m_p the proton rest energy, and $p_{p\parallel}$ the component of the recoil proton momentum parallel to the incident neutron direction.

In Figure 3 we have plotted the GEANT4 computed energy distribution histograms obtained for the SONTRAC detection of 500000 normal incident neutrons at 50 MeV (solid line) and at 100 MeV (dashed line). The energy bins are $0.5MeV$ wide.

We obtain an energy resolution of $\sim 3\%$ at 50 MeV and $\sim 6\%$ at 100 MeV. We define the detection neutron efficiency at $50MeV$ as the ratio between the total counts in the energy range 40-60 MeV and the total amount of incoming neutrons. For the neutron efficiency at 100 MeV we take into account counts in the energy range 90-110 MeV. With these definitions the neutron detector efficiency of a $10 \times 10 \times 10cm^3$ polystyrene block in the single np scattering mode is $\sim 6\%$ at $50MeV$ and $\sim 2\%$ at $100MeV$.

3.2 Double np elastic scattering detection mode

To explain the reconstruction of the incident neutron energy and direction from double recoil proton tracks, we refer to the schematic view plotted in Figure 2. We have to determine which of the two registered tracks correspond to the first recoil proton $p1$. It can be shown that after an elastic scattering the neutron momentum is nearly perpendicular to the recoil proton momentum. From the starting positions of the two scintillating tracks we deduce the momentum direction of the neutron after its first scattering ($n1$). The first recoil proton $p1$ is the one whose the track direction is nearly perpendicular to momentum of $n1$. If none of the two recoil proton tracks is nearly perpendicular to the momentum of $n1$ we reject the event. Knowing the energy and momentum of $p2$ and the momentum direction of $n1$ we compute the energy of $n1$ with the use of equation 1. By adding together the momentum of $n1$ and $p1$ we obtain the momentum and therefore the energy of the incident neutron.

In Figure 4 we have plotted the GEANT4 computed energy distribution histograms obtained for the SONTRAC detection in the double np elastic scattering mode of 500000 normal incident neutrons at 50 MeV (solid line) and at 100 MeV (dashed line). The energy bins are 0.5 MeV wide.

We obtain an energy resolution of $\sim 3\%$ at 50 MeV and $\sim 3\%$ at 100 MeV. We consider for the detector efficiency the same definition as used in the single scattering mode. The neutron detection efficiency of a $10 \times 10 \times 10cm^3$ polystyrene block is in the double np elastic scattering mode $\sim 0.57\%$ at $50MeV$, and $\sim 0.14\%$ at $100MeV$

3.3 nC inelastic scattering mechanism

At around 50 MeV the nC inelastic scattering mechanism starts to dominate the elastic one. A good knowledge of the nC inelastic scattering physics is therefore needed to improve detector efficiency of SONTRAC at energies higher than 50 MeV. In our simulations we have used the GHEISHA model built in GEANT4. However a more precise model than GHEISHA is probably needed to model properly the hadronic physics in the energy range 50-250 MeV.

4 Conclusion

We have developed a Monte Carlo GEANT4 application for modeling the SONTRAC neutron detector. We have computed the proton range in the SONTRAC scintillating fiber block for energies $\leq 110\ MeV$. The computed range are significantly higher than measurements of the SONTRAC scientific model. In the future we plan to better model the composition of non-core materials of the scintillating fibers. This is crucial for understanding the discrepancy between range computation and measurements.

We have also simulated the detection of 500000 incident neutrons at 50 and $100 MeV$, by a $10 \times 10 \times 10 cm^3$ SONTRAC scintillating block. For the energy resolution we obtain:

– Single np elastic scattering mode
  – $3\ \%$ @ $50 MeV$
  – $6\ \%$ @ $100 MeV$
– Double np elastic scattering mode
  – $3\ \%$ @ $50 MeV$
  – $3\ \%$ @ $100 MeV$

A rough estimate of the detector efficiency is

– Single np elastic scattering mode
  – $6\ \%$ @ $50 MeV$
  – $2\ \%$ @ $100 MeV$
– Double np elastic scattering mode
  – $0.57\ \%$ @ $50 MeV$
  – $0.14\ \%$ @ $100 MeV$

To improve the SONTRAC neutron detection efficiency at energies higher than 50 MeV a hadronic shower model other than GHEISHA is probably needed for the simulation of the nC inelastic scattering.

Acknowledgements. This study was supported by the Swiss National Science Foundation, grant 2000-057175.99, and by the ESA ESTEC contract 14982/00/NL/PB.

References

ENDF, Evaluated Nuclear Data Files W3 Retrieval System, http://www-nds.iaea.or.at/endf/endfframe.html, 2001.

Fesefeldt, H., GHEISHA The Simulation of Hadronic Showers, 149 RWTH/PITHA, 85/02, 1985.

GEANT4, the GEANT4 toolkit, http://wwwinfo.cern.ch/asd/geant4/geant4.html, 2001.

Jungerman, J. A. and Brady, F. P., A medium-energy neutron facility, Nucl. Instr. and Meth., 89, 167-712, 1970.

Miller, R. S., SONTRAC MEMO, private communication, 2001.

Romero, J. L., Brady, F. P., Needham, G. L., Castaneda, C. M., Subramanian, T., Ullmann, J. L. and Zanelli, C. I., Electron capture by protons in a neutron beam facility, Nucl. Instr. and Meth., 171, 609-612, 1980.

Ryan, J. M., Castaneda, C. M., Holslin, D., Macri, J. R., McConnell, M. L., Romero, J. L., and Wunderer, C. B., A scintillating plastic fiber tracking detector for neutron and proton imaging and spectroscopy, Nucl. Instr. and Meth. in Phys. Res., A 422, 49-53, 1999.

Wunderer, C. B., Feasibility study of SONTRAC- a neutron tracking telescope for solar, atmospheric and other applications, Master Thesis, University of New Hampshire, 1997.