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Land-surface studies with a directional neutron detector

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Abstract

Direct measurements of cosmic-ray neutron intensity were recorded with a neutron scatter camera developed at SNL. The instrument used in this work is a prototype originally designed for nuclear non-proliferation work, but in this project it was used to characterize the response of ambient neutrons in the 0.5-10 MeV range to water located on or above the land surface. Ambient neutron intensity near the land surface responds strongly to the presence of water, suggesting the possibility of an indirect method for monitoring soil water content, snow water equivalent depth, or canopy intercepted water. For environmental measurements the major advantage of measuring neutrons with the scatter camera is the limited (60°) field of view that can be obtained, which allows observations to be conducted at a previously unattainable spatial scales. This work is intended to provide new measurements of directional fluxes which can be used in the design of new instruments for passively and non-invasively observing land-surface water. Through measurements and neutron transport modeling we have demonstrated that such a technique is feasible.

CONTENTS

1. Introduct ion

Water at the land surface plays a critical role in atmospheric, hydrologic and ecological processes. Water can be stored at the land surface in the form of soil moisture and snow, and just above the land surface on vegetative canopies and in plants themselves. The observation of land-surface water in its various forms is critical to rainfall-runoff modeling, stream flow forecasting, ecoclimate, vegetation dynamics, hill slope stability, surface and ground water interactions, drought monitoring and prediction, fire hazard assessment, and weather prediction. However, despite its widely-recognized importance, observations of land-surface water have been difficult to obtain at a scale commensurate with the process of interest. This has been a major obstacle to both fundamental and applied research in earth and atmospheric sciences.

A growing recognition of the importance of land surface processes has motivated large investments in remote sensing technologies in recent years–particularly in space-borne active and passive microwave sensors. Both NASA and the European Space Agency (ESA) have launched major remote sensing initiatives (SMAP and SMOS, respectively) over the past several years (SMAP, 2008), with combined investments totaling over $1.5B. Despite these large investments, several challenges will likely remain. For example, methods to calibrate and ground truth these instruments over a wide area are widely acknowledged to be lacking. Furthermore, the microwave method provides only shallow penetration in soil (several millimeters), whereas knowledge of soil moisture in the root zone (tens of centimeters) is usually preferred by hydrologists and ecologists. And although the satellite research programs include land-surface modeling initiatives intended to provide extrapolations to the root zone, it is not yet clear if and how those models will be validated with field data. Satellite technology, as currently conceived, has other limitations, including sensitivity to vegetation, dew and surface roughness. However, the biggest limitation is the spatial scale, which is approximately 40x40 km for passive microwave. While this is an acceptable scale for global observations, most hydrologic and ecological processes will continue to be studied at smaller scales.

The directional neutron detector such as the neutron camera could provide a viable method for monitoring land-surface water across a diameter of meters to several tens or even hundreds of meters. The method would measure the transmission of neutrons through soil, snow or forest canopy as a proxy for equivalent water depth. The source of these neutrons is cosmic-ray interactions with soil and atmospheric neutrons. The scatter camera has several advantages: it is passive, non-invasive, mobile, non-destructive, insensitive to soil chemistry and would average over a scale unattainable by conventional instruments. Such a method could provide a much needed ground truthing method for soil water and biomass measurements from satellites, and could be used for studying the dynamics of moisture in and in plants, and soil moisture in the shallow root zone. Data collected with the scatter camera will also support development work being done with other cosmic-ray hydrometric techniques, or in the development of application specific directional detectors for environmental observations.

This project was partly motivated by a unique opportunity to leverage significant investments by the Office of non proliferation research and development (NA-22) and the Defense threat reduction agency (DTRA). Construction and development of the neutron scatter camera was funded by NA-221 and DTRA, and the instrument and expertise for this project were already largely in place. The goal of this project is to direct this technology toward new applications that could have a significant impact on earth and atmospheric sciences. The neutron scatter camera is a unique instrument, and likewise may provide unique opportunities for research in land-surface studies.

2. THEORY

2.1. Cosmic-ray neutrons

Cosmic-ray neutrons are an ever-present component of the land-surface radiation environment. They are tertiary by-products of chain reactions initiated at the top of the atmosphere by primary cosmic rays. A simulated particle cascade created by a 10 GeV primary interacting with nitrogen is shown in Figure 1. The primary radiation is composed of highly energetic particles, mainly protons and helium nuclei, which are believed to have been accelerated in shock waves associated with supernovas occurring throughout the Milky Way. Energetic primaries collide with atmospheric gas molecules, unleashing cascades of secondary protons, neutrons and other subatomic particles, some of which penetrate to sea level.

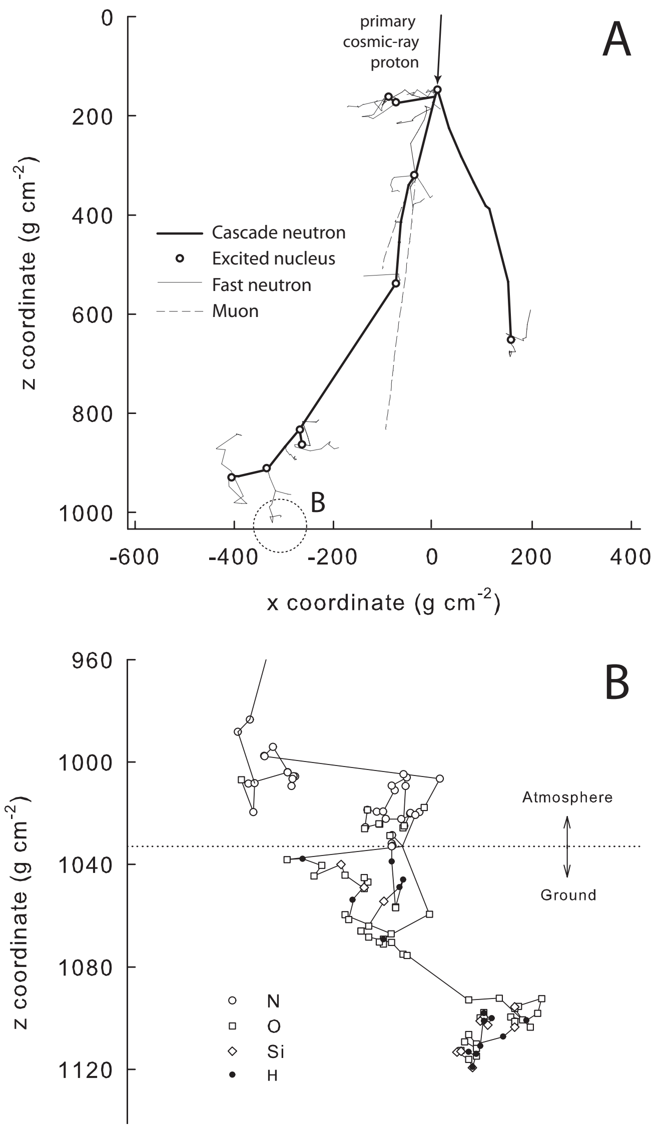

Figure 1. Atmospheric particle cascade simulated with the radiation transport code MCNPX. Fast neutrons are generated at each collision marked by a circle. The fast neutrons are scattered in random directions as they are moderated and eventually become captured.

The neutrons utilized for passive water content measurements are generated mainly by cascade neutrons interacting with matter. Fast neutrons are produced mainly in two types of interactions. A cascade neutron can transfer kinetic energy to an entire target nucleus, raising it to an excited energy state. The nucleus then cools off by “evaporation”, i.e. the emission of fast neutrons in random directions. Cascade neutrons with higher energies will tend to interact at the surface of a nucleus, dislodging the outer most neutrons in a mostly forward direction. Fast neutrons produced through these mechanisms are scattered elastically in random directions until they are eventually absorbed by soil or atmospheric nuclei.

2.2 Neutron intensity at the land surface

Fast neutron intensity at the land surface reflects an equilibrium between production, moderation and absorption of neutrons in the ground and atmosphere (Figure 2). Neutrons are scattered between the ground, which tends to be the better moderator when wet, and the atmosphere, which is a better thermal neutron absorber. Any change in water content at the land surface disturbs this equilibrium. An increase in the amount of soil water or snow decreases the intensity in the fast to epithermal region because neutrons are more efficiently reduced to lower energies through collisions with hydrogen.

As shown in Figure 2, the sensitivity of neutron fluxes to water content is nearly the same over several log decrements of energy, but sensitivity is reduced at energies above 1 MeV and below 1 eV.

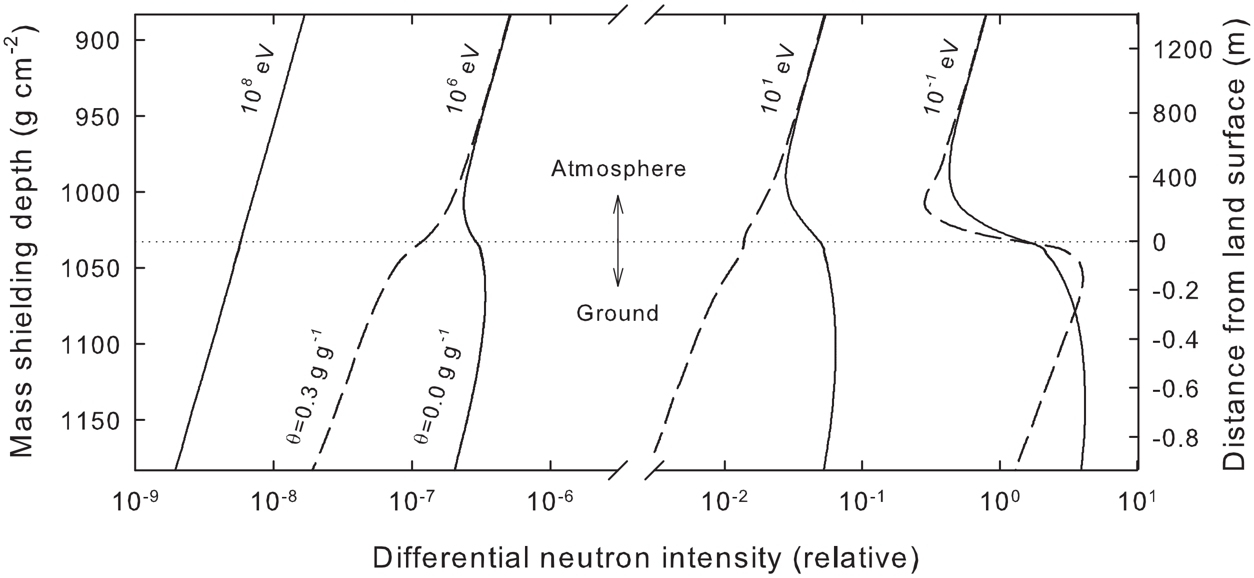

Figure 2. Depth profiles of neutron intensity near the land surface for different energies simulated with MCNPX. Between 10^1-10^6 eV, where elastic scattering interactions dominate, the shape of the profile and its sensitivity to soil moisture are remarkably constant. At lower energies (<10^{-1} eV), thermal neutron absorption becomes important and the shape of the profile reflects the strong contrast between the absorbing properties of the ground and atmosphere. At higher energies (>10^8 eV) the profile reflects exponential attenuation expected for cascade neutrons.

2.3 Measuring neutron intensity with a neutron scatter camera

The neutron scatter camera used in this experiment measures the direction and energy of neutrons between 1 and 10 MeV over an approximate 60 degree field of view (Mascarenhas et al., 2006). The instrument consists of cells of liquid-scintillator (EJ301) and co-located photomultiplier tubes arranged in two parallel planes (Figure 3). To calculate the initial direction of an incident neutron, the camera uses conservation of energy and momentum for the collision between an incident neutron. The incident neutron scatters in the first detector plane and then again in the second detector plane. The angle of the first scatter ($_1$) is related to the energy given to the proton in the first scatter, E_p, and the energy of the scattered neutron, E_{n1}, as:

$$\tan^2 \theta_1 = \frac{E_p}{E_{n1}} \quad 1$$

The proton recoil energy is measured directly from the detector output and the energy of the recoiling neutron is determined from the time-of-flight (TOF) between the two detector planes according to

$$E_{n1} = \frac{m}{2}\left(\frac{d}{TOF}\right)^2$$

where *d* is the separation between detector planes. Because the direction of the recoiling proton in not measured, only the ring defined by the initial scatter angle $_1$ is determined. This defines a probability cone which can be back projected onto a virtual image plane. An image is formed by overlapping these cones over many events. In addition, the energy of the incident neutron is obtained as the sum of the two measured energies E_p and E_{n1}, providing an accurate neutron spectrometer.

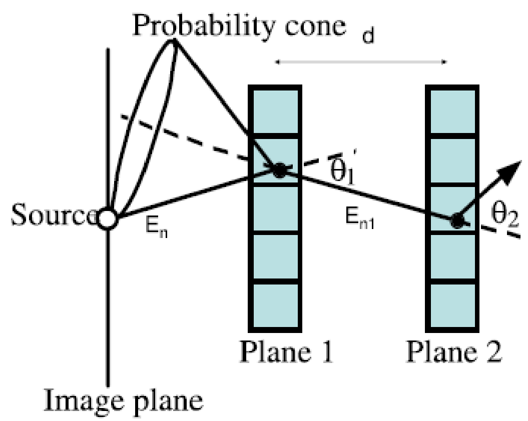

Figure 3. Schematic of neutron scatter camera.

3. EXPERIMENTAL METHOD

3.1 Measurements at TEAMS

All measurements were performed at the DTRA Technical Evaluation and Assessment Site (TEAMS) facility on Kirtland Air Force Base in Albuquerque, New Mexico. The coordinates of the site are 35.037° N and 106.450° W, the elevation is 1634 m above sea level, and the mean barometric pressure is approximately 834 mb. Electronics (NIM, VME, racks and data acquisition computer) were housed in a 40 ft. steel sea land container (Figure 4A) that had been used in a previous investigation of neutron intensity aboard shipping vessels. The data recorded in this experiment allow for the determination of fluxes for

- Forward (coincident) neutrons.
- Backward (coincident) neutrons.
- Single (non-coincident) neutrons in either detector plane.
- Forward gamma rays.
- Backward gamma rays.
- Forward muons.

Barometric pressure and temperature were recorded from inside of the container with a *Heavyweather* weather station. Barometric pressure data are also available from numerous weather stations operated throughout the Albuquerque area.

Two sets of measurements were taken. First, neutron intensity was recorded from inside of the container with the scatter camera looking upward. A galvanized-steel stock tank (2.4 m in diameter) was placed on top of the container directly over the scatter camera. Measurements were taken with the tank filled to various levels of water up to a maximum nominal depth of 50 cm. Water depth was measured at a radius of 0.6 m in eight directions (four cardinal and four intercardinal directions).

The second set of measurements was taken with the scatter camera and stock tank relocated to a tent adjacent to the container (Figure 4). The instrument was positioned in the center of the stock tank and pointed downward so that upward neutron intensity was recorded in the forward mode. The lower detector plane located approximately 20 cm above the bottom of the tank. Measurements were taken with the tank filled to various levels of water up to a maximum nominal depth of 25 cm. Water depth was measured at the each of the four outside corners of the scatter camera and four intermediate locations.

Table 1. Record of Neutron measurement at TEAMS, 2008-09.

Filenam		e	Depth [cm]	Start	Finish
Upward looking	CHP00 0			30-Aug-08	3-Sep-08
	50cm		47.3	10-Sep-08	26-Sep-08
	40cm		40.0	26-Sep-08	16-Oct-08
	30cm		30.1	16-Oct-08	7-Nov-08
	20cm		20.0	7-Nov-08	17-Nov-08
	10cm		9.1	17-Nov-08	3-Dec-08
	5cm		5.0	3-Dec-08	29-Dec-08
	2cm		1.9	29-Dec-08	26-Jan-09
	0cm		0.0	26-Jan-09	29-Jan-09
	50cm	-b	48.8	29-Jan-09	13-Feb-09
	35cm	-b	36.3	13-Feb-09	18-Feb-09
	20cm	-b	20.4	18-Feb-09	23-Feb-09
Downward looking	0cm-down 0.0			22-Apr-09	7-May-09
	3cm	-down	2.4	7-May-09	12-May-09
	6cm	-down	7.2	12-May-09	14-May-09
	10cm	-down	10.9	14-May-09	18-May-09
	15cm	-down	16.2	22-May-09	19-May-09
	25cm	-down	25.8	19-May-09	23-May-09

Figure 4. (A) Contai ner and tent from which upw ard and dow nward looking measurements were r espectively taken. (B) Neutron scatter camera taking downward measurements from inside of tent at a water depth of 0 cm.

3.2 Monte Carlo simulations

Land-surface neutron fluxes were simulated using the numerical transport code Monte Carlo N-Particle-eXtended (MCNPX). Source particles were neutrons with energies between $4\text{x}10^2$ MeV and $5\text{x}10^4$ MeV and a spectrum following Ziegler (2000). Source neutrons originated from a planar source with a $\cos^3\theta$ angular distribution and were propagated through 200 g cm^{-2} of atmosphere (ρ= $1.22\text{x}10^{-3}$ g cm^{-3}) before reaching the land surface. The ground was assumed to be a 6 m layer of silica soil. The water layer was modeled as a semi-infinite slab and angular fluxes from 0 to 60^{o} (120 to 180 ^{o}) were recorded as surface tallies below (above) the pool. An accurate detector model has also been created in MCNP-PoLiMi and additional simulations will be conducted.

4. RESULTS AND DISCUSSION

4.1. Upward-looking measurements

Both measured and simulated fluxes indicate a sharp decrease in intensity with the first 10 cm of water followed by a more gradual decrease with additional water. This may be explained as a transition effect. Low-energy neutrons in equilibrium with atmospheric production are rapidly filtered out in the first 10 cm of water, but beyond 20 cm fluxes have re-equilibrated to the lower rate of production and higher rate of absorption water. Neutron production decreases with depth due to the exponential attenuation of the generating component.

The modeled fluxes (Figure 5) indicate that the shape of the neutron profile changes rapidly with energy between 0.3 MeV and 10 MeV, suggesting the need for instrumental energy sensitivity to be well characterized for rigorous comparisons with modeling. The modeling also suggests that the sensitivity to water depth can be more than doubled in the first 10 cm by lowering the energy threshold to below 1 MeV. The improved sensitivity is probably a consequence of the energy dependence of the elastic scattering cross section for hydrogen, which decreases rapidly with increasing energy from 1 to 100 MeV. However, because the scattering cross section is nearly constant between 0.01 and 1 MeV, the sensitivity should not increase much at these energies, whereas gamma discrimination would become increasingly problematic.

This experiment demonstrates that measurements of canopy intercepted water or snow are feasible using ambient fast neutron fluxes. Given the pulse shape discrimination characteristics of liquid scintillators used in neutron counting, and given the modeled sensitivities (Figure 5), the optimal detector for observing overlying water would have a peak response in the range of 0.3 to 1 MeV.

What are typical depths of canopy intercepted water? This varies widely given the vegetation type, the physical state of precipitation (rain or snow), and meteorological conditions. Flux tower and precipitation measurements (Molotch et al., 2007) indicate that a montane, mixed conifer forest in Northern New Mexico can hold the equivalent of several millimeters of water following a snow storm. This snow is typical removed from the canopy by sublimation or melting within several days to a week following the storm. Changes in water equivalent depth on the order of

0.5 to 1 mm can probably be resolved using fast neutrons. With measurements in the 0.3-1 MeV range, the sensitivity over the first 2 mm of water is 1.2 % mm^{-1}. Considering only counting statistics, achieving 4-hour temporal resolution with a precision of 0.5 mm (1σ) should be easily obtainable at mountain altitudes over a 60° field of view using conventional detector technology. Given the difficulty of partitioning canopy from understory sublimation using conventional methods, cosmic-ray measurements appear to be viable alternative.

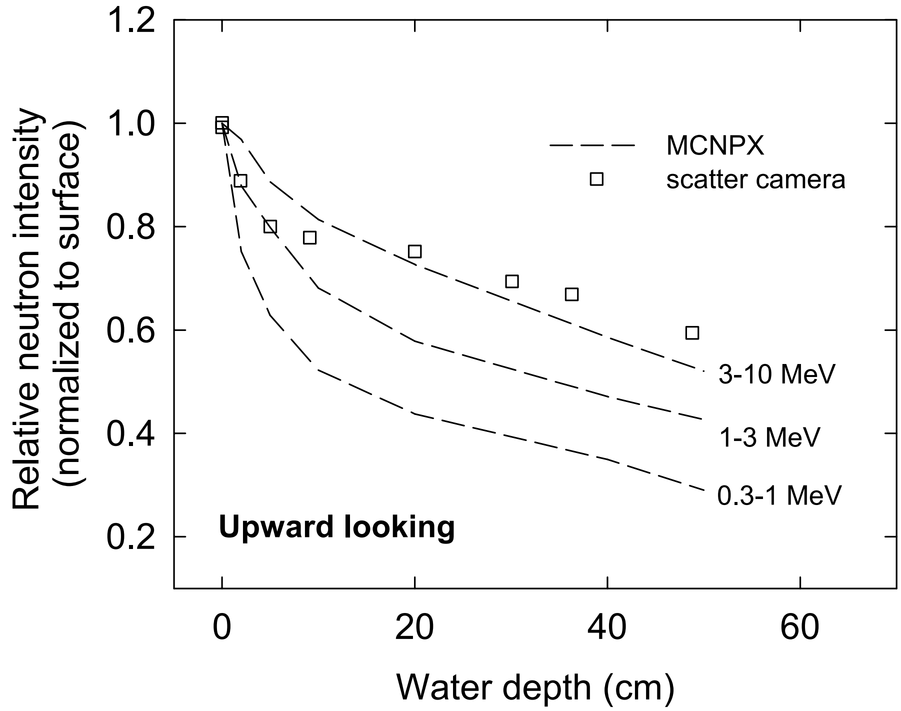

Figure 5. Forward neutron fluxes measured with the upward-looking scatter camera and modeled in MCNPX. All fluxes are normalized to a water depth of 0 cm. The forward count rate at 0 cm was 1370 counts d^{-1}.

4.2. Downward-looking measurements

The downward-looking fluxes show a dependence on water depth similar to what was found with the upward-looking measurements. As was with the upward fluxes, neutron intensity decreases most rapidly with the first several cm of water (Figure 6). However, there is a significant discrepancy between the measured and modeled fluxes. Transport modeling suggests that neutron intensity should be nearly constant at depths greater than 10 cm, whereas measurements indicate that neutron intensity continues to decrease following an e-folding length of about 100 cm. We are currently investigating potential causes for the discrepancy. It could be related to a problem in our MCNPX simulation. One possibility is a deficit of upward moving neutrons in the 10-50 MeV energy related to the selection of an intranuclear cascade model. The possibility of instrumental drift is also being investigated. For example, a gain shift on photomultiplier tube amplifiers could account for the problem.

It is worth noting that the e-folding length of 100 cm for the tail end of the curve is close to the scattering mean free path length for neutrons in the 1-10 MeV range. This supports the possibility of a physical explanation for the unexpected attenuation as opposed to a systematic instrumental bias that is by coincidence correlated to water depth. If the effect is real, this suggests that the upper limit to non-invasive measurements of snow water equivalent depth could be several tens of centimeters or more, making the range of application several times greater than we had predicted with MCNPX. It also suggests a significant flux of penetrating, upward directed neutrons that could be utilized in the investigation of subsurface objects or voids in the top several meters of soil.

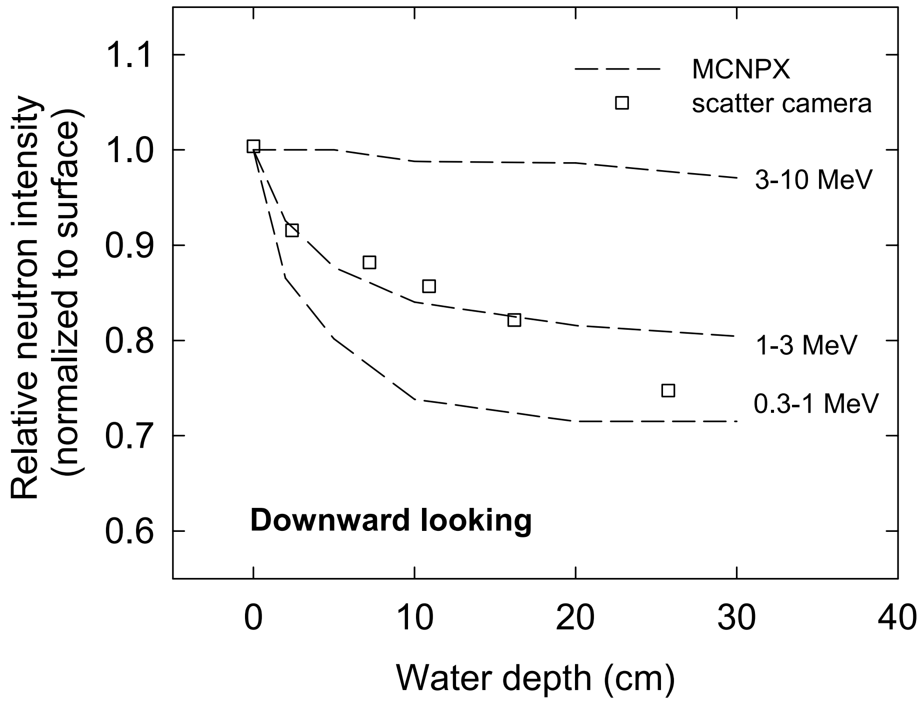

Figure 6. Forward neutron fluxes measured with the downward-looking scatter camera and modeled in MCNPX. All flux es are normalized to a w ater depth of 0 cm . The forw ard count rate at 0 cm was 1400 counts d^{-1}.

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