Cosmic-ray neutron probe: non-invasive measurement of soil water content

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DESCRIPTION

We are developing a novel technique for soil water content determination that operates on the horizontal scale of dekameters. The method is based on the same principle that underlies conventional neutron probes: thermalization of neutrons by hydrogen atoms (see **BASIS OF THE METHOD**). The standard neutron probe works by emitting fast neutrons from a source in the instrument, and measuring the flux of neutrons that are scattered back. Our new probe uses a similar detector, but has cosmic-ray neutrons as a source (see **COSMIC RAYS ON EARTH**).

Coupling neutron detectors with cadmium and polyethylene shielding (see **INSTRUMENTATION**) changes the energy sensitivity of the instrument, and thereby also the sensitivity to water content. Results from a series of laboratory and field experiments show that our cosmic-ray probe is capable of measuring changes of water content resulting from irrigation or infiltration after a storm event (see **EXAMPLE**). Our numerical **SENSITIVITY** experiments indicate that 1% change in volumetric water content corresponds to between <1% and 17% change in neutron flux, depending on neutron energy and soil water content. Neutron intensities are sensitive to water in the upper 10-100 cm of soil and over a footprint of 10-100 m in diameter (see **FOOTPRINT**). Both the depth and the footprint decrease with the increasing soil water content.

Our method has five useful characteristics:

(1) It can be non-invasive and non-contact, allowing for broad coverage of undisturbed soil conditions;

(2) It does not contain a radioactive source, so it can be transported easily and left in the field unattended;

(3) It can be automated (computerized) easily;

(4) It can be deployed below or above the ground surface;

(5) It measures soil water at an intermediate scale of tens of meters.

The cosmic-ray neutron probe can be used jointly with other techniques, thus bridging the gap between small-scale point measurements and satellite imaging. In this fashion, it can be used to calibrate remote sensing instruments.

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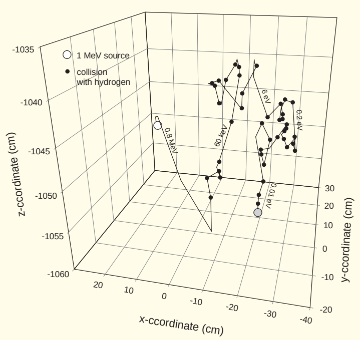
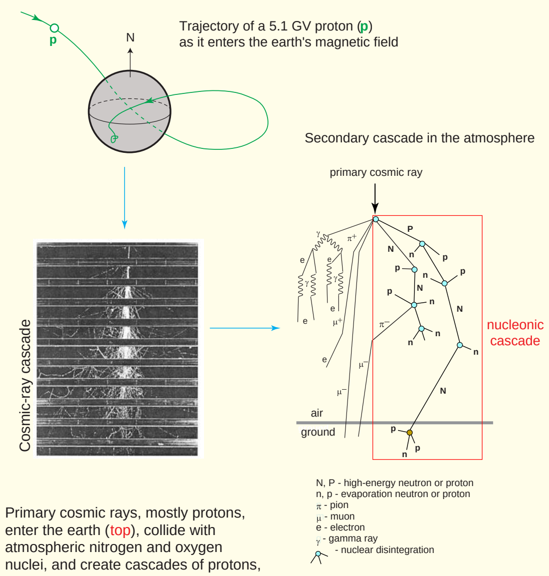
1. BASIS OF THE METHOD



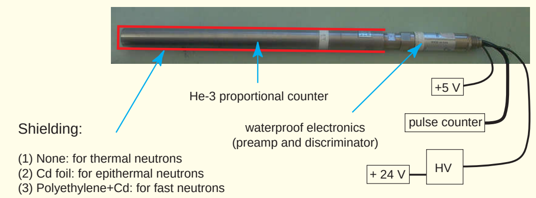
Cosmic-ray fast neutrons are produced in the ground when cosmic-ray particles collide with nuclei. These neutrons are moderated (slowed) through elastic collisions, lose energy, and eventually become thermalized. The energy loss is inversely proportional to the atomic weight of nuclei. Because the efficiency with which hydrogen thermalizes neutrons is very high, the number of low-energy neutrons depends strongly on the hydrogen content of the soil, and thus on its water content.

2. COSMIC RAYS ON EARTH



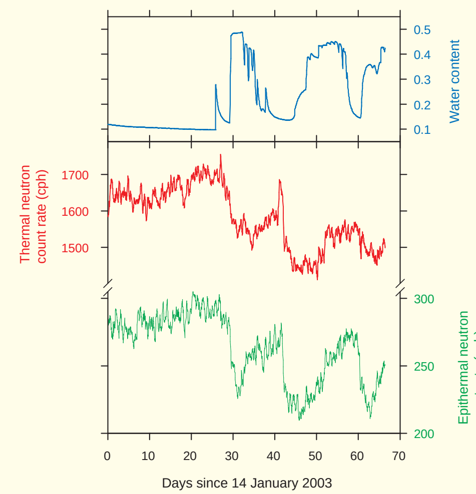
Primary cosmic rays, mostly protons, enter the earth (top), collide with atmospheric nitrogen and oxygen nuclei, and create cascades of protons, neutrons and other secondary particles (photo and diagram on the left). Many energetic secondary particles penetrate the atmosphere and interact with terrestrial nuclei. These interactions generate neutrons at the earth's surface. These secondary neutrons are the source of fast neutrons that are used in our cosmic-ray probe.

3. INSTRUMENTATION



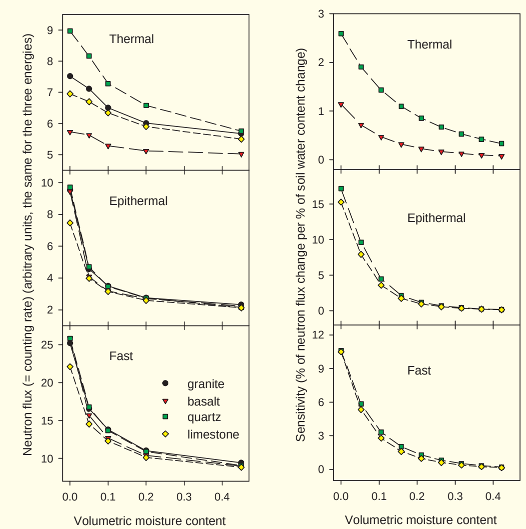
Neutrons are detected using proportional counters (photo above). Detectors are placed on or above the ground (photo to the right), which results in the footprint of tens of meters. However, detecors can be placed below the ground for smaller measurement volume.

4. FIELD EXAMPLE



Field measurements of soil moisture content using time domain reflectometry (TDR) and thermal and epithermal neutron fluxes using neutron detectors revealed a clear relationship between soil moisture and neutron intensity. The first decrease in neutron fluxes is due to a rain event (day 30); the second (day 42) and third (day 60) are due to snow melt following two snow storms. The magnitude of the change of neutron intensity is consistent with theoretical predictions (see SENSITIVITY), indicating that our knowledge of neutron response to variable soil water content is adequate.

5. SENSITIVITY



Explanation:

Left: variations of neutron counting rates (fluxes) with soil water content for four representative parent rocks.

Right: Sensitivity of the neutron counting rate to soil water content calculated as derivatives of the functions in the left panels.

Observations:

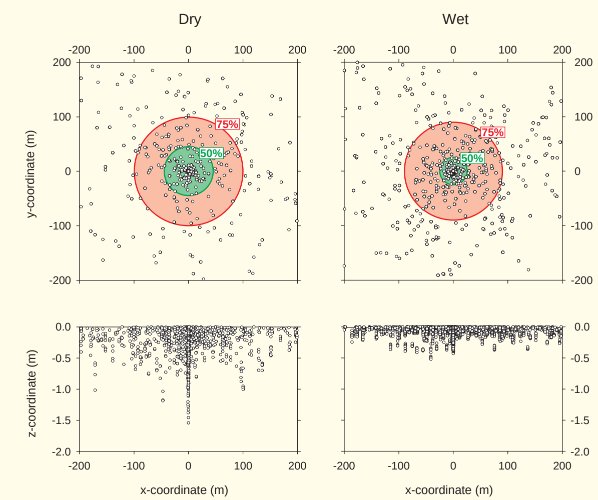
(1) Thermal neutrons have lowest sensitivity to water; epithermal have highest.

(2) Thermal neutrons are sensitive to rock chemistry; epithermal and fast are not.

(3) Sensitivity is highest at low water contents.

(4) Fast neutrons have the best combination of sensitivity and absolute counting rate for soil water content measurement.

6. FOOTPRINT



Measurement area (footprint) and thickness for dry and wet silica sand (100% SiO2), calculated using (Monte Carlo N-Particle (MCNP) code for epithermal neutrons. Both the footprint and thickness decrease with increasing soil water content.