On-site Neutron Logging for Cultural Heritage Applications:

A Monte Carlo Study

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Abstract: Neutron logging is a nuclear technique based on measurements of gamma radiation emitted from soil and rocks under neutron irradiation. The gamma radiation yields information on the materials present in the irradiated volume and, in principle, can be used to sample unexcavated area and spot the presence of buried archeological artifacts. In this paper, we investigate the feasibility of the technique for applications in cultural heritage by using Monte Carlo techniques. A simulation model of a neutron logging system is developed and used to predict the sampling volume and the gamma ray energy distribution emitted by a region of soil containing a buried copper sample. Results show that the sampling volume is approximately 1.6 x 1.5 x 1.7 m^3 when a 14 MeV neutron source is simulated. In addition, gamma ray energy spectra obtained with and without the copper sample with a 100% efficient detector are presented. Additional gamma peaks, generated by the interaction of the neutrons with copper, are visible when the sample is introduced. Changes in the spectral lines are a clear indication of the presence of additional chemical elements in soil, and can be used to reveal the presence of materials hidden in soil, as, for instance, archeological artifacts.

Keywords: Geant4, Monte Carlo simulation, Neutron logging, Cultural Heritage.

Introduction

The need to non-destructively localize buried archeological artifacts prior excavation, thus reducing the number of unnecessary excavations and/or the damage to hidden artifacts, becomes more and more stringent. A possible solution could be found in neutron logging, a nuclear technique commonly employed to investigate underground soil and find metal, mineral, gas, and oil deposits (KILLEN 1997, WIELOPOKSKI et al. 2005). The technique involves the use of a source of neutron radiation and a radiation detector lowered in a borehole. The neutron logging method is based on the measurement of either the original radiation, which has been modified by the physical properties of the material around the borehole through which it traveled, or the secondary radiation emitted after excitation by the primary source radiation (KILLEN 1997). The first method is commonly referred to as neutron-neutron method, the latter as neutron-gamma method. At present the source of neutrons in most neutron logging systems is a neutron generator. Neutron generators produce intense monoenergetic neutron fluxes, can be used in pulse mode, and are easily transportable and stored in that they are turned off when not in use (REICHARDT et al. 2001, IAEA 1999). Neutrons generated by the neutron generator are slowed down through inelastic and elastic scattering with the nuclei of the material surrounding the borehole and are eventually absorbed. Gamma radiation, yielding information on the material around the borehole, is produced during these processes and, in the neutron-gamma method, is measured by a radiation detector. The detector can be a simple monitor to count the gamma rays or a spectrometer to measure their energies (REICHARDT et al. 2001). The processes involved in the production of gamma radiation are radiative neutron capture and inelastic scattering. The radiative neutron capture reaction consists of the absorption of a neutron by a nucleus and the emission of one or more gamma rays (FODERARO 1971). This gamma radiation is emitted at specific energies characteristic for the different chemical elements. Often the product nucleus formed in a neutron capture reaction is unstable against radioactive decay. It decays usually by the emission of a beta particle and decay gamma rays (FODERARO 1971). The inelastic scattering consists of the interaction of a neutron with a nucleus and results in the excitation of the internal state of the nucleus. This excited nucleus usually emits one or more gamma rays to reach its ground state (KILLEN 1997). The inelastic scattering reactions can happen only above a given energy, characteristic of the target material (MOLNAR 2004), whereas neutron capture reactions primarily happen at low neutron energies. Measured gamma-ray spectra contain gamma ray lines from each of the above mentioned interactions, thus include peaks resulting from inelastic scattering of fast neutrons, thermal neutron capture, and delayed activation. The low gamma ray flux and the large number of peaks result in peak interferences and misidentification (BODNARIK 2013). To lessen these issues we exploited the pulsed nature of the neutron generator that produces neutrons in short bursts. The gamma rays that result from the inelastic scattering of the 14 MeV neutrons will occur only during the time of the burst. Between each burst, the materials around the borehole moderate the fast neutrons so that the gamma rays are produced by neutron capture. After most of the thermal neutrons have been absorbed the gamma ray results from delayed activation. Separating the gamma rays by their interaction time relative to the neutron generator pulse results in a substantial reduction in peaks interferences (BODNARIK 2013). The information given by the gamma radiation following neutron irradiation may be used in archeology to find elements normally absent in soil, revealing the presence of buried archeological artifacts. Computer simulations based on Monte Carlo radiation transport techniques, which long have been used by scientists involved in nuclear reactor shielding design and radiation dosimetry, perhaps provide the best methods to study the feasibility of a new logging concept (SMITH et al. 1981) and its application to a new field of research.

In this paper, we investigate the application of the neutron logging technique to cultural heritage, focusing on the neutron-gamma method, by using Monte Carlo radiation transport techniques. We describe a simulation model of a planned neutron logging system. The system is comprised of a neutron source and a gamma ray detector contained in an aluminum cylindrical housing approx. 1 m in length and 10 cm in diameter. We present the sampling volume for a 14 MeV neutron generator. The sampling volume defines the volume from which we can extract useful information. In addition, we present the simulated gamma ray energy distribution emitted by a soil volume where an archeological artifact (represented by a simple copper sample) is buried.

Methodology

We investigate the capability of the neutron-gamma logging technique to reveal the presence of buried objects by using the Geant4 Monte Carlo code (AGOSTINELLI et al. 2003, ALLISON et al. 2006). In the proposed neutron logging system, a pulsed neutron generator of 14 MeV is used to irradiate the soil around a borehole and a gamma ray detector is used to measure the inelastic scattering, capture, and activation gamma ray energies. In order to study the feasibility of the method, aside from detector effects, we modeled an ideal detector with efficiency of 100%. The neutron logging system can measure a wide range of elements, i.e. C, H, O, P, S, Si, Na, Ca, Ti, Fe, Al, Cu, Cl, Ag, Au, Mg, Mn, K, Th, U, depending on their abundance in the irradiated volume and interference of any neighboring gamma ray peaks (BODNARIK 2013). To study the feasibility of this method experimentally would be time consuming and costly, requiring the construction and testing of a neutron logging system (SMITH et al. 1981). The situation is well suited to investigation by Monte Carlo techniques. Neutron and gamma ray transport through complex geometrical configurations can be simulated accurately using Monte Carlo techniques. The method consists in following a large number of particles from their source positions as they are scattered or absorbed by materials in the given geometry (SMITH et al. 1981).

Fig. 1 shows the simulated configuration of the neutron logging system inside a borehole. It consists of a neutron generator and a gamma-ray detector. The neutron generator is a 14 MeV neutron point-like source with a 10 degrees side aperture. The detector with dimensions of 6.4 cm in diameter and 9 cm in length is placed 50 cm above the neutron source. Source and detector are contained in a 1 mm thick aluminum housing. The borehole has a diameter of 11 cm and a depth of 2 m. The simulated soil chemical composition is shown in Tab. 1 (HOOVER et al. 2009). The soil density is 1.5 g/cm^3. A copper sample with a diameter of 5 cm and a length of 20 cm is placed at 13 cm from the central axis of the borehole and at a depth of 103 cm to show the capability of the system to reveal buried samples. The neutron source was simulated by starting neutrons of 14 MeV at time t=0 at the center of the borehole at a depth of 130 cm with direction randomly sampled in a cone of 10 degrees aperture along the z-axis. Neutrons tracks were followed through the simulated geometry until they were absorbed. Neutrons were slowed down by elastic and inelastic scattering prior absorption. In an inelastic scattering, simulated with the Geant4 high precision neutron model, one or more gamma rays were generated at the location of the interaction. The process of neutron capture modeled in Geant4 was modified and gamma rays of energies randomly sampled from the nuclear decay schemes taken from the Evaluated Nuclear Structure Data File [TULI 2001] were simulated at the interaction point. If the compound nucleus, generated by the absorption of the neutron, was unstable, the decay gamma rays were produced with the nucleus characteristic half-life using the Geant4 radioactive model. The gamma rays produced by inelastic scattering and neutron capture were tracked in the geometry and allowed to interact via photoelectric effect, Compton effect, and pair production. Positrons from pair production were tracked till annihilation and gamma rays of 511 keV were produced at the annihilation position. Energy and measurement time were recorded for every gamma ray detected during the data acquisition and stored in a ROOT (BRUN et al. 1996, BRUN et al. 1997) file. To separate the data into gamma ray spectra from neutron capture and better identify gamma ray lines and elements present in soil, we selected gamma ray events with time in the [1μs-10ms] time window.

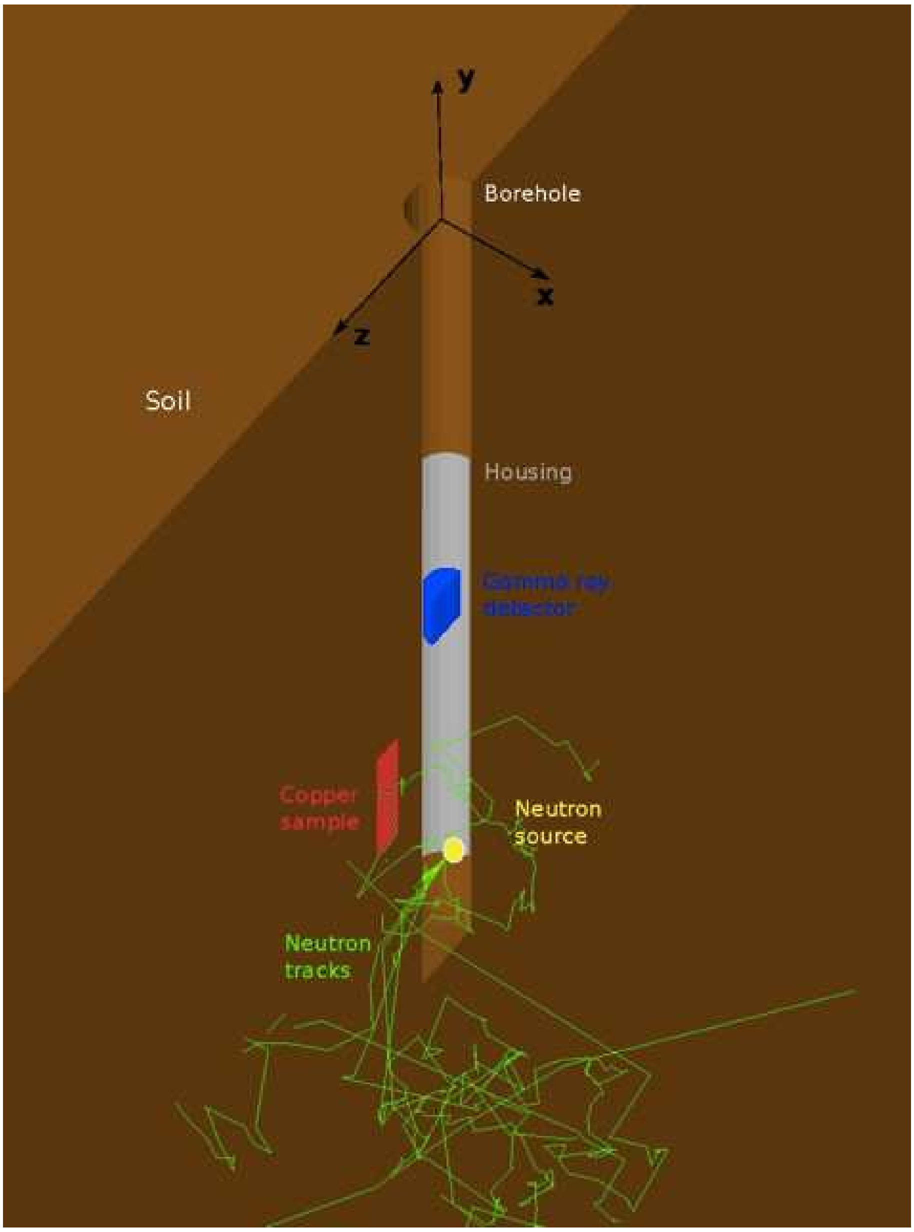

Fig. 1 – Geant4 model of the neutron logging system. Gamma detector (blue), neutron source (yellow), and logging system housing (gray) inside the borehole, and copper sample (red) buried in the soil (brown) are illustrated. The green lines indicate the neutrons interacting with the soil and the sample. The visualization was generated with the Geant4 DAWN and DAWNCUT visualization tools.

Element	Percentage
H	2.1
C	1.6
O	57.7
Al	5.0
Si	27.1
K	1.3
Ca	4.1
Fe	1.1

Tab. 1 – Composition of simulated soil (HOOVER et al. 2009).

Results

The simulated neutron range in soil for a 14 MeV neutron generator with a 10 degrees side aperture is shown in Fig. 2. Ten million histories were simulated. The neutron point source was located at the center of the borehole at a depth of 130 cm. The neutron range is 110 cm in the direction of emission of the neutrons and 60 cm in the opposite direction. The neutron range is 80 cm along the x and y axes. No primary radiation reached the surface of the borehole. Fig. 3 shows the time distribution of the gamma rays produced by inelastic scattering, neutron capture, and delayed activation. To select the neutron capture gamma rays and reduce gamma ray line identification issues we selected gamma ray events in the time window [1 μs –10 ms]. Fig. 4 shows the simulated neutron capture gamma ray spectra for the 14 MeV pulsed neutron generator and the gamma ray detector having efficiency of 100% with and without copper sample. As expected, additional peaks from copper are visible when the sample is introduced.

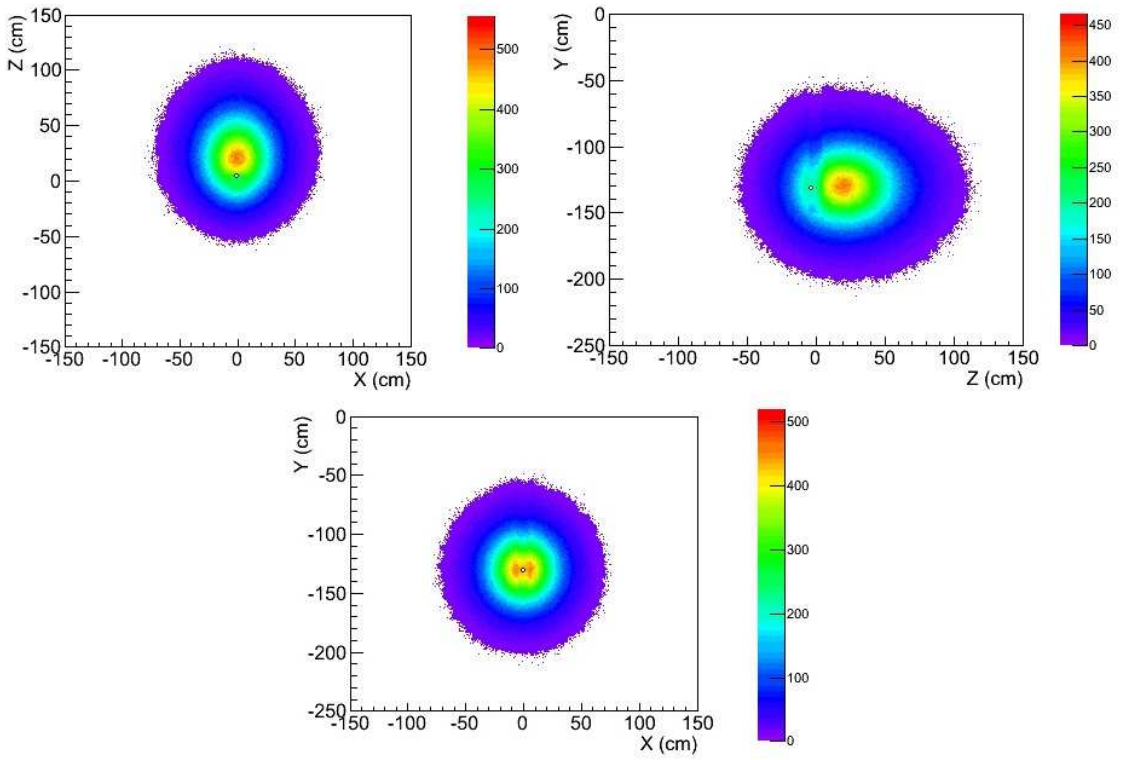

Fig. 2 – Simulated neutron end point in soil for a 14 MeV neutron generator. The white circle indicates the position of the neutron source. Top left: Neutron end point in the horizontal plane (xz plane). Top right: Neutron end point along the y and z axes (yz plane). Bottom: Neutron end point along the x and y axes (yx plane).

Tab. 2 lists gamma ray energies from capture of neutrons in different elements present in soil and in copper in the range 6.5-8 MeV. All the gamma ray lines listed in Tab. 2 are visible in the spectra, except for the Cu line at 6989 keV that is buried in the K peak at 6999 keV, and the Cu line at 7637 keV buried in the Fe peaks at 7631 and 7646 keV. This technique provides information on the elemental composition of the irradiated volume, in this case the soil area. It could be used to reveal the presence of elements not contained in soil, and, in principle, spot the presence of buried objects, as, for instance, archeological artifacts. Detailed studies of gamma ray energy spectra measured by different types of detectors are needed. Future work is planned to model the detector response and optimize the system design for cultural heritage applications, in terms of material and size of the gamma ray detector and distance between neutron source and detector. In addition, the detection limits of the system will be evaluated for chemical elements commonly found in archeological artifacts.

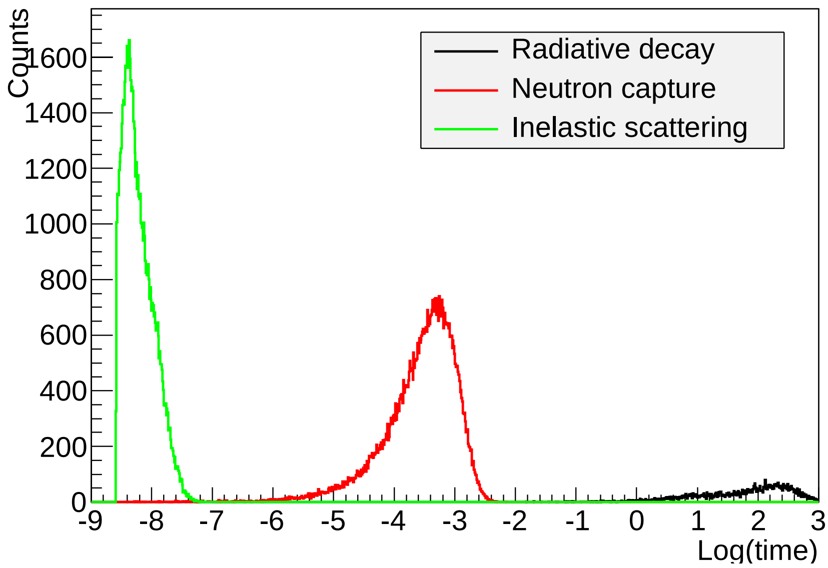

Fig. 3 – Time distribution of gamma rays produced by inelastic scattering, neutron capture, and delayed activation following neutron irradiation.

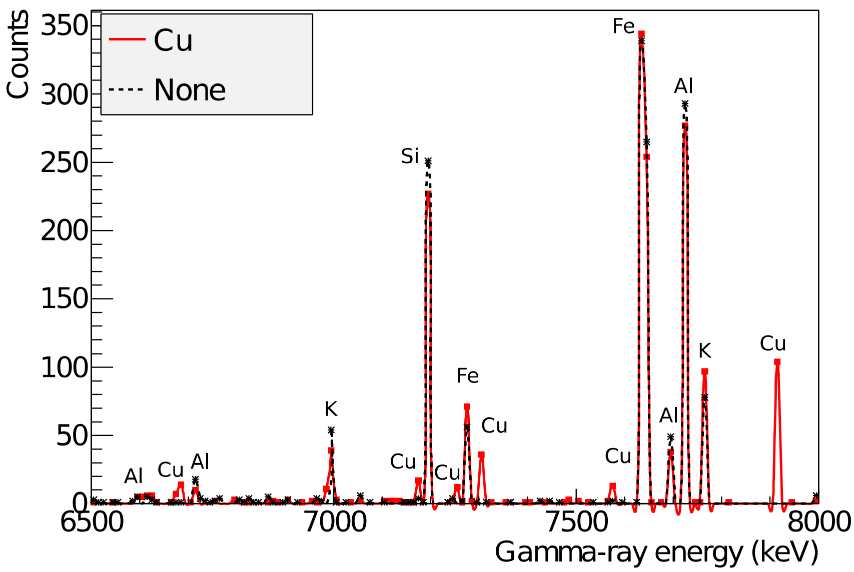

Fig. 4 – Comparison of simulated neutron capture gamma ray spectra emitted by a soil volume with (solid red line) and without (black dashed line) copper sample in the energy region 6.5 MeV – 8 MeV. Fifty million histories were simulated. Contributions from the Cu element are clearly visible.

Element	Peaks (KeV)
Al	6620, 6711, 7693, **7724**
Si	7199
K	6999, **7769**
Fe	7279, **7631**, 7646
Cu	6680, 6989, 7253, 7303, 7637, **7916**

Tab. 2 – Gamma ray energies from capture of neutrons in different elements present in soil and in copper in the range 6.5-8 MeV. Numbers in bold are the energies of the strongest peaks. [MOLNAR 2004].

Conclusions

The application of the neutron logging technique to the field of cultural heritage has been investigated. The technique, which is based on measurements of gamma radiation emitted under neutron irradiation, provides information on the chemical composition of the irradiated material. Theoretically such technique could be used in archeological sites to provide elemental composition of the irradiated volume, spotting the presence of buried archeological artifacts. A neutron logging system consisting of a neutron generator of 14 MeV and a gamma detector with efficiency of 100 % has been studied with Monte Carlo techniques. Simulation results predict a sampling volume of 1.6 x 1.5 x 1.7 m^3. Energy spectra of gamma rays from neutron capture have been simulated by selecting gamma ray events in the 1 μs - 10ms time window. Additional spectral peaks can be seen in the simulated gamma ray energy spectrum when a copper sample is present in the irradiated volume. These peaks can be used as indicators of the presence of extraneous material in soil. The simulated data indicate that the use of a neutron logging system in an unexcavated site, where an area of interest has been identified, could provide information on the presence of chemical elements not contained in soil and, in principle, reveal buried archeological artifacts. In addition, the neutron logging technique could yield information on the stratigraphy of archeological sites, since it provides in situ information on bulk elemental abundances. As other nuclear techniques, neutron logging implies a collaboration between physicists and archaeologists when employed in archeological sites. Future work is planned to build a more detailed model of the system and to predict the detection limits of the technique.

Acknowledgments

Computing resources of the Science and Technology Facilities Council's e-Science facility (UK) were used in this research.

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Imprint:

Proceedings of the 17th International Conference on Cultural Heritage and New Technologies 2012 (CHNT 17, 2012)

Vienna 2013

http://www.chnt.at/proceedings-chnt-17/

ISBN 978-3-200-03281-1

Editor/Publisher**:** Museen der Stadt Wien – Stadtarchäologie

Editorial Team: Wolfgang Börner, Susanne Uhlirz