A NEW INTENSE NEUTRON TOOL FOR RADIOGRAPHY AND DETECTION OF WATER AND GROUND CONTAMINANTS

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Abstract

Advances in ion sources and gamma ray detection at LBNL are being applied to enhance neutron logging tools. A rf-driven plasma ion source has been miniaturized to the 2 inch diameter necessary for most underground uses. The ion current produced is >80% monatomic, and is projected to produce a neutron flux of 10^9 - 10^{10} neutrons/sec, an enhancement of 1-2 orders of magnitude over the state-of-the-art. A 1.5 x 1.5 x 1 cm^3 CdZnTe gamma detector is also being developed for the tool. This detector has relatively high efficiency, good energy resolution, and room temperature operation. Results of 3-D Monte Carlo calculations are presented which show the enhancements in sensitivity and range possible with the new technology.

1. INTRODUCTION

Compact sources of neutrons are used for neutron activation analysis, radiography, and for detection of water, oil, and minerals in the subsurface. One common example is the use of neutron logging tools, 2-4 inches in diameter and a few meters in length, in the oil industry and in earth science research. These tools consist of a Penning ion source and ~100 kV accelerator column, which accelerates a mixture of deuterium and tritium ions onto a tritiated target, producing 14 MeV neutrons. Detectors in the tool measure returning neutrons, and gamma rays produced by neutron capture and inelastic scattering of neutrons from the elements of the medium. The energy of the gamma rays produced by these processes is characteristic of the nuclei impacted, enabling, in theory, an elemental analysis of the medium. In practice, the gamma-ray spectrum is often crowded with spectral lines, so that what can be detected depends heavily on the energy resolution of the gamma-ray detector and the cross section of the element being detected.

In this paper we report improvements in the components (ion source, accelerator, and gamma-ray detector) of such a neutron logging/gamma-ray spectroscopy system. The results of 3-D Monte Carlo modeling of the enhanced system for new earth science applications will also be presented. The MCNP code [1] has been used to quantify the advantages in instrument range and sensitivity resulting from the enhanced neutron flux. Calculations have also been used to look at the possibility of 3-D localization of detected substances.

2. ION SOURCE AND ACCELERATOR

For this project a LBNL radio-frequency-driven ion source was miniaturized to an overall diameter of 2 inches. The ion source and accelerator are described in detail in another paper in these proceedings (L.T. Perkins et al.), but a summary directed to the application will be given here. The source consists of a cylindrical volume of plasma 2.5 cm in diameter and 9 cm in length. The beam is extracted through a 2 mm aperture in the extraction electrode. Miniaturization has required the reduction of source operating pressure in order to avoid electrical breakdown in the accelerator column. The source presently runs well at 5 mTorr.

A helical rf antenna 1.5 cm in diameter is used to generate the plasma. Because of the difficulty of miniaturization, the rf power supply will be located above ground. Presently, cable losses limit source use to depths less than about 500 feet.

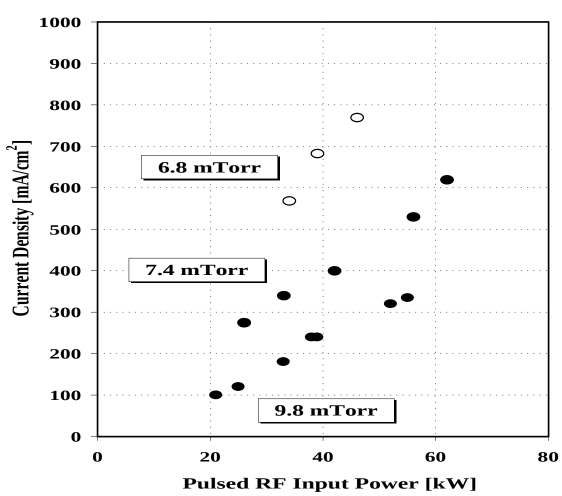

Figure 1. Peak extractable current density at three different source pressures, versus rf input power.

Measured current density is shown in Fig. 1 as a function of input rf power. The ion current densities measured are about a factor of 500 higher than those in commercial neutron logging tubes. Up to 35 mA/pulse has been produced, and this current can be increased by simply opening the 2 mm extraction aperture, since current is linearly proportional to aperture area. Minimum pulse width is about 8 μs. The beam is largely monatomic, with monatomic fraction increasing with increasing rf power. At 40 kW, the beam is 80%

monatomic, and 94% at 60 kW. (For details, see L.T. Perkins et al., in these proceedings.) The monatomic fraction is particularly important because these ions will have nuclei with energies double that, for instance, of diatomic nuclei, and therefore are closer to the optimum energy for neutron production. Based on the data presented, we project a yield of 10^9-10^{10} D-T n/s, or 10^7-10^8 D-D n/s, at pulse rates ≈ 1 kHz. A test of neutron production in a commercial neutron tube will be performed within the next 6 months.

A 100 kV accelerating system has been designed, using the IGUN© code to obtain the shape, potential, and positions of the accelerating electrodes. A suppresser electrode is included to minimize backstreaming electrons. This also removes ambiguity in ion current measurements. The accelerator design will minimize sputtering and produce uniform beam spreading on the target, leading to longer tube lifetime. The accelerator is presently in fabrication.

3. GAMMA-RAY DETECTOR

For well logging applications, gamma ray detection is usually done with scintillation detectors (e.g., NaI), or, to a lesser extent, with cryogenically-cooled germanium. For this project, we have chosen to develop a detector based on the compound semiconductor material CdZnTe, because of its high efficiency, good energy resolution, and the promise of room temperature operation. The problem of poor charge transport in this material has recently been overcome by the development of the coplanar-grid technique [2], which uses the subtraction of signals from two interdigitated grids to make detector response largely insensitive to the depth of gamma-ray interactions. Using this technique, an energy resolution of ~2% FWHM for 662 keV gamma rays has been achieved for 1 cm^3 CdZnTe detectors operating at room temperature [3][4]– a factor of three higher than the resolution of NaI. Resolution better than 1% FWHM (662 keV) is in principle possible [3].

Though the high thermal neutron capture cross section of Cd would normally be a problem in this application, calculations have shown that a thin layer of $^{10}B_4C$ can provide adequate neutron shielding for the detector. Another issue of some concern is detector radiation damage. Fast neutrons can damage the crystal lattice of the detector, degrading the charge collection properties and adversely affecting its energy resolution. Currently, only very limited experimental data exists on the effects of neutron damage in CdZnTe detectors [5]. More studies are needed in this area to determine whether CdZnTe detectors, and particularly those using the coplanar-grid technique, are suitable for this application.

CdZnTe detectors are currently limited to volumes of 1-2 cm^3, mainly due to material nonuniformity. However, because of the high atomic number of CdZnTe, the photopeak efficiency is equivalent to that of a substantially larger Ge or NaI detector, and the small size is advantageous in the limited space of the borehole. MCNP calculations show the efficiency of CdZnTe to be about three times that of the same volume of NaI or Ge in the energy range of interest [6].

The goal of the present work is to develop CdZnTe coplanar-grid detectors of approximately 2 cm^3 volume and energy resolution ≤1% FWHM for the energies of interest (≈ 1-10 MeV). Figure 2 shows the spectral performance of a 2.25 cm^3 detector made for this project. Energy resolution at 1.33 MeV is 1.6% FWHM. The detector was slightly cooled (to approximately -10ºC) to reduce its leakage current so that higher bias voltages could be used. At room temperature, noise due to leakage current would dominate and significantly degrade the energy resolution. The high bias was needed to minimize the effects of nonuniform charge collection in the crystal. Room temperature operation with similar or better performance can be achieved if crystals with better uniformity are available. Alternately, further improvements in the fabrication process may lead to lower leakage current so that room temperature operation at high biases is possible without excessive leakage-current noise. A prototype hermetic detector module containing the detector and front-end electronics has been fabricated. Power consumption of the front-end electronics is less than 150 mW.

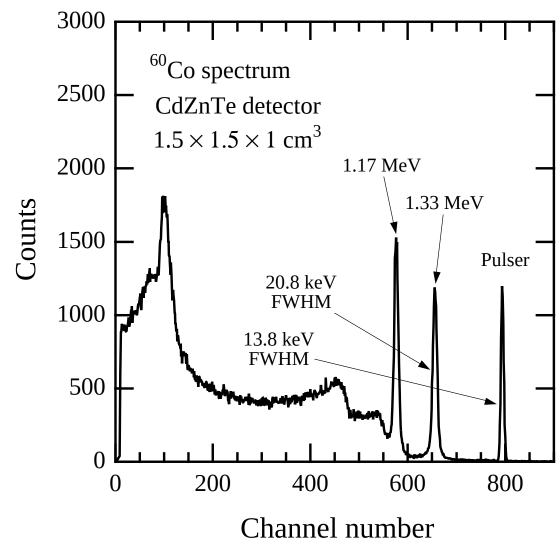

Figure 2. Spectrum of ^{60}Co obtained using a coplanar-grid CdZnTe detector operated at a temperature of approximately -10ºC and at a detector bias of 1600 V.

4. MODELING

The 3-D point-energy time-dependent Monte Carlo code MCNP with the ENDL60 [7] cross section library has been employed to model use of the enhanced-flux neutron logging tool with a CdZnTe detector. Previous results have shown the utility of this method for detection of water and for chlorinated solvents, which are widespread pollutants [6]. Note that all gamma-ray spectra calculations quoted here are simulations of measurements for 14 MeV neutrons taken with the detector gated off during the neutron pulse and the 30 μs following the pulse. This is a standard technique for eliminating counts due to inelastic scattering of fast neutrons.

We present here MCNP results showing the advantages of increased source intensity for increased range of the instrument. To measure range we assume the level of minimum detectability to be 2.33σ above background [8], where σ is the standard deviation of the background counts. In the model, fractures were formed using two infinite parallel planes. Vertical fractures intersecting the center of the borehole were generally used. Very little difference was found between horizontal and vertical fractures through the borehole. Calculations showed that for 1 g/cm^3 TCA in a 1 cm-wide fracture, for 1000 second counting times, the range increased from 50 to 70 cm as source intensity increased from 10^7 to 10^9 neutrons/sec. For the same fracture filled with 0.3 g/cm^3 NaCl in water, the increase was from 40 to 60 cm, an increase of 50%. In both cases the 6.11 MeV chlorine capture line was used. The detector efficiency is not included in these calculations. For 1% detector efficiency, range decreases for the TCA to 20 cm at 10^7 n/s, and 40 cm at 10^9 n/s.

A few cases have been run to determine the effect of neutron flux on minimal detectable concentration. For TCA uniformly spread through wet sand (30% water), 2 ppm TCA is detectable with 10^7 n/s, and 0.5 ppm with 10^9 n/s.

We have begun to investigate the possibility of 3-D localization of detected materials. As neutron borehole tools are used today, readings are taken vs. depth, giving only location in the vertical dimension. With increased flux, some azimuthal photon collimation can also be done, without decreasing the signal below the limits of detectability. To model this, a 1 cm^3 spherical CdZnTe detector was assumed to be at the center of a 5 cm radius borehole. The detector was surrounded by a spherical tungsten collimator shell 3.88 cm thick. A neutron shield consisting of a 0.5 cm-thick spherical shell of $^{10}B_4C$ enclosed the detector/collimator. A 0.6 cm diameter horizontal cylindrical hole through the collimator, aimed at the detector center, allowed photons to enter the detector. A vertical fracture 1 mm wide, filled with water containing 0.3 g/cm^3 NaCl, intersected the borehole. Signal intensity vs. collimator position is shown in Fig. 3, as the collimator is rotated around the borehole axis. The fracture is at 0°. The photon energy spectrum is measured at the center of the detector using an MCNP biased point detector tally. The detector efficiency has not yet been taken into account. Results are shown for the 2.23 MeV gamma ray from hydrogen capture as well as the 6.11 MeV and 7.42 MeV gammas from capture in chlorine. The best results, from the 6.11 MeV line, indicate a signal-to-noise ratio of about 8. These results for such a small fracture size are quite promising. Analyses are underway to investigate the effects of collimator size and material, composition of media and fracture, and detector energy response.

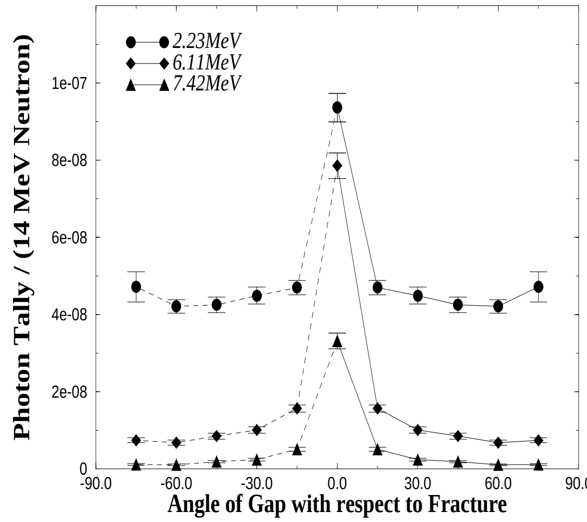

Figure 3. Calculated angular response to a 1 mm fracture in dry granite, filled with water containing 0.3 g/cc NaCl. Photon yields are normalized to the response at 0 degrees (collimator aligned with fracture).

5. ACKNOWLEDGEMENTS

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