HIGH SENSITIVITY SUBSURFACE ELEMENTAL COMPOSITION MEASUREMENTS WITH PING.

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Introduction: The Probing In situ with Neutrons and Gamma rays (PING) instrument will measure the bulk elemental composition of the subsurface (0.3 – 1 m) of any solid solar system body and is a versatile, effective tool for a host of scientific investigations, including detailed local geochemistry analysis, and the search for astrobiological niches. A proposed instrument for inclusion in the Mars 2020 science payload, PING would also excel at precision surveys of subsurface materials for sample analysis and selection for sample return missions.

PING would enhance the science return of myriad future landed missions. Due to the penetrating nature of its high-energy neutrons and gamma rays, PING could see through the walls of a landed Venus probe. PING would neither need to be deployed nor would samples need to be brought into the probe for PING to perform its analysis as part of a Venus In Situ Explorer. The PING technology is ideally suited for *in situ* analysis and sample return missions to the Moon, the surface of a comet, NEOs, as well as for Mars sample return missions. In fact, PING can play an important role in any landed portion of the future Mars program. PING is thus a versatile instrument that will fill an important niche in NASA's Planetary Science Exploration Program.

Instrument Technology Description: PING consists of a pulsed neutron generator (PNG), a Gamma Ray Spectrometer (GRS), and neutron detectors. 14 MeV neutrons emitted isotropically from the PNG penetrate the surface to a depth of ~ 1 m and interact with the material to produce characteristic gamma rays with energies specific to the isotopes involved. Detected lines in the resulting gamma ray spectra indicate which elements are present and the line intensities measure the quantity of each element. See Figure 1 for an illustration of the gamma-ray generation process when using a PNG.

Fast PNG neutrons that interact via elastic scattering in the soil are slowed and can emerge from the surface as albedo neutrons. The time and energy distribution of the albedo neutrons are primarily indicative of the hydrogen content and its layered structure.

Neutrons interacting in the soil through inelastic neutron scattering and neutron capture give rise to gamma rays on different time scales between the PNG pulses. Time-tagging the individual gamma ray events with respect to the PNG fast neutron pulse provides additional analysis tools.

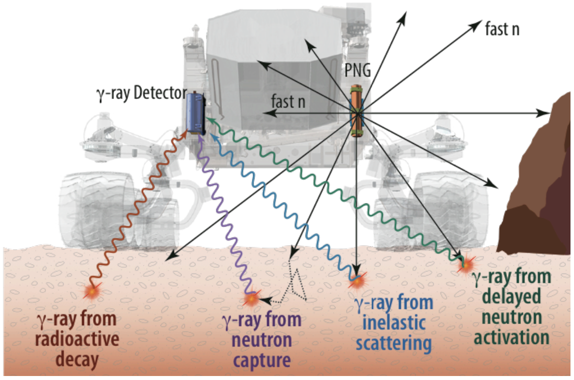

Figure 1. PING's PNG excites the nuclei in the Martian soil resulting in the emission of characteristic gamma rays. The detection of the characteristic gamma rays analyzed by the GRS yields the elemental composition.

Thus measuring both gamma ray and neutron time and energy spectra characterizes different properties of the planetary regolith. Combining the two measurements in one instrument is highly synergistic, for the analysis of each influences the analysis of the other. For example, the regolith density measured by neutron detection affects the gamma ray detection efficiency from a given material, and the elemental composition determined by the gamma rays affects how neutrons slow or are moderated, by the material. Establishing regolith composition through a self-consistent analysis of *both* gamma ray *and* neutron spectra enables measurements superior to those provided by instruments containing only gamma ray or only neutron spectrometers. A hybrid gamma ray and neutron detector can be created by wrapping the gamma ray detector in materials such as Cd and ^{10}B. The absorption of thermal and epithermal neutrons by these materials will produce specific gamma rays that are detectable by the surrounded GRS. The hybrid detector is thus sensitive to gamma rays, epithermal and thermal neutrons. Such hybrid schemes are very useful when separate neutron detectors would take more resources than are available for a particular mission.

The PING technology builds on the principles behind the Dynamic Albedo of Neutrons (DAN) instrument on the Mars Science Laboratory (MSL). DAN uses some of the same principles as PING, but since it is missing the crucial gamma ray component, it can only infer the existence of hydrogen, while PING can determine the complete quantitative elemental composition of H, C, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Fe, Th, and U.

The technology choices for the three components and their efficient coordination into a single instrument system determine the ultimate performance of PING. The choice of neutron generator is especially important since it must be tuned to operate well with the gamma ray spectrometer, both during the pulse and in-between pulses. Since the timing of the neutron and gamma ray data between bursts is affected by the presence of high neutron scattering materials such as hydrogen, it is important to be able to alter the PNG pulse width and pulse period to accommodate any changes in material composition it encounters in different locations. A high neutron emission rate is also important because it reduces the time needed for each measurement. A long-lived, high rate PNG with complete flexibility in pulse width and pulse frequency is thus crucial to the effective implementation of this technique. The DAN PNG lifetime is short and its flexibility in pulse timing and rate is too limited for it to be practical for use with a gamma ray spectrometer.

Operational Advantages and Capabilities: The ~1 m penetration depth of the PNG neutrons allows an assay of subsurface composition without the need for extracting samples. Because the fast neutrons are emitted isotropically, the measurement volume is approximately a ~1 m radius hemisphere beneath PING. Averaging over this volume reduces the effects of small highly localized anomalies. PING thus produces the bulk elemental composition of a given location and provides chemical context for measurements by other types of instruments.

For example, since X-rays are much less penetrating than high-energy gamma rays, familiar X-ray instruments such as APXS and XRF can only probe a small shallow spot on the surface (~few mm radius, ~100 microns deep). Since PING has access to the same elemental composition information, X-ray and gamma ray instruments are quite complementary – especially when identifying and characterizing surface effects.

PING measurements of elemental composition can also be used to infer mineralogy and can be valuable as a check on the mineralogical interpretations of infrared spectroscopy results. Moreover, the interpretation of neutron-only measurements is highly composition dependent. The addition of gamma ray data quantifies the composition and allows quantitative H concentrations as well.

When placed on a rover, PING can be sent out as part of a robotic reconnaissance mission to quickly map an area, searching for the best locations to find material for either sample selection for sample return missions or In Situ Resource Utilization (ISRU). Quick-look PING analysis would provide near-real time results, informing rover operational decisions.

Computer Simulations and PING Sensitivity Estimates: PING was proposed for inclusion in the Mars 2020 payload as an instrument that could measure subsurface elemental composition and indicate the most favorable locations for taking samples to be placed in a returnable cache. To that end, sophisticated computer simulations were performed to determine PING's sensitivity both in "active mode" with the PNG on and in "passive more" where the PNG is turned off and the fast neutrons are produced by Galactic Cosmic Ray (GCR) interactions and the rover's Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) power source. We will present the results of these simulations to show how quickly PING can determine relevant subsurface compositional changes.

The gamma ray energy distribution and flux of the neutrons that produce them depends on the particle source energy distribution (GCR, MMRTG, or PNG) and the elemental composition of the regolith. Neutron-transport codes are commonly used to calculate the GCR-generated neutron spectrum and the resulting flux of inelastic-scatter and capture gamma rays that escape from a planet's surface. PING's expected sensitivities are based on model calculations using the Monte Carlo N-Particle eXtended (MCNPX) radiation transport code [1-3] routinely used for such simulations. Sensitivities were calculated both for the active mode (PNG neutron source) and for the passive mode (MMRTG and GCR neutron source). Model calculations for PING active measurements assume a source neutron energy of 14.1 MeV, a pulse width of 100 μs, pulse period of 1000 μs, and 10^5 neutrons per pulse. Passive measurements, other than for the radioactive nuclides (K, Th, U), depend on the GCR spectrum and/or the spectrum of neutrons from the MMRTG. In all cases, the Martian atmosphere and an MSL rover model [4] were part of the calculations, contributing to the gamma ray signal. The position of the PING neutron generator and detector used in the model was the same as for the DAN instrument on MSL [5]. The elemental abundances simulated are derived from the reference Martian basalt composition from Blake et al. [6] containing 1 wt% water equivalent hydrogen. The calculated observation durations for significant science return for each element are based on 2σ statistical uncertainties. Differences between the test values and those obtained on Mars will be largely due to systematic errors that include, for example, errors in the model description of the rover (geometry and material composition) compared to the actual rover.

We will present the minimum detectable changes in elemental abundances that the team deems necessary for useful science ("geological insight") and the observational durations needed to achieve sensitivity to these thresholds in PING's active and passive modes. The threshold for each element is based either on the variability in the abundance of the element previously observed on Mars in both orbital and landed geochemical measurements, or on the precision to which the abundance of the element must be known to achieve useful geochemical classifications. For example, the abundance of S in the reference basalt is 2.25%. It is expected that a minimum fractional change of 3.5x is needed for useful science based on the ability to sense lithified sulfate. Calculations show PING will be able to detect this change at a 2σ level by observing for only 9 minutes in active mode or 313 minutes in passive mode.

An essential aspect of the PING instrument is the ability to "see" below the surface. The 14.1-MeV PNG neutrons provide this capability because of their high flux and high energy. The MMRTG neutron peak flux is at ~3.1 MeV [4] and modeling shows these neutrons do not penetrate the surface to depths of more than a few cm with sufficiently high numbers to provide any useful subsurface elemental information from gamma-ray measurements. However, the subsurface thermal neutron flux produced by the MMRTG does provide a sensitive measure of elements such as H and Cl. Higher H abundance produces higher thermal neutron fluxes, because it is so efficient at thermalizing neutrons, while higher Cl reduces thermal neutron flux because of its high capture cross section. These computer simulations were validated with data taken during PING prototype tests at GSFC. Earlier work with a PING prototype performed at a unique neutron generator test site at GSFC showed excellent agreement between experimental results and Monte Carlo simulations [7, 8].

Conclusions: PING, a combination of PNG and gamma and neutron spectrometers, is a promising instrument for measuring the full bulk elemental composition of the near subsurface of any rocky body in the solar system. The PING neutron/gamma instrument is highly adaptable to a large variety of mission roles and is a valuable complement to commonly used instrument technologies. Mineralogy instruments such as infrared spectrometers benefit from PING's elemental context information to eliminate some of their interpretation ambiguities. X-ray instruments, which only measure surface composition, benefit from subsurface measurements from PING so that surface and bulk effects on soils can be separated. A final benefit is that PING can make its measurements without needing to drill or even contact the surface. Thus, a rover-mounted PING can quickly map the full elemental composition of large areas.

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