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Development of a Low-Resource Combined Gamma-Ray and Neutron Spectrometer for Planetary Science

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ABSTRACT

Planetary neutron and gamma-ray spectroscopy (NGRS) has become a standard technique to measure distinctive geochemical composition and volatile abundance signatures for key elements relevant to planetary structure and evolution. Previous NGRS measurements have led to the discovery of the concentration of many elements including hydrogen on the Moon, Mars, Mercury, and the asteroids Eros, Vesta, and Ceres, but by utilizing separate NGRS. We have developed the Elpasolite Planetary Ice and Composition Spectrometer (EPICS) instrument, an innovative and combined NGRS with low resource requirements. EPICS incorporates elpasolite scintillator read out by silicon photomultipliers (SiPMs) to provide significant reduction in size, weight, and power, while achieving excellent neutron detection sensitivity and gamma-ray energy resolution as good as 2.9% full-width half-maximum at 662 keV. EPICS is ideally suited to resource constrained missions and is applicable to numerous targets such as the Moon, Mars, and small planetary bodies. An overview of the EPICS instrument and its simulated performance on a few notional missions is presented. We have integrated and done performance testing of a prototype of the EPICS instrument, including optimization of an amplification and summing circuit for a 64-element SiPM array that preserves pulse shape discrimination capability, which will be summarized.

INTRODUCTION

Planetary neutron and gamma-ray spectroscopy (NGRS) is a well-established technique for studying the geochemical composition of planets or solid bodies such as moons or asteroids. As illustrated in Figure 1, on airless or near airless bodies galactic cosmic rays (GCRs) interact with matter in the top tens of centimeters to one meter of planetary surfaces to produce spallation neutrons. Moderation of these neutrons by hydrogen provides a unique signature indicating the presence and abundance of near-surface water that can be in the form of hydrated minerals or water ice. Gamma rays are produced at characteristic energies either by radioactive decay of natural elements or the interaction of neutrons with matter. These characteristic gamma rays indicate the presence and abundance of most major and minor rock-forming elements, including H, C, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Fe, Th and U. These unique neutron and gamma-ray signatures can be measured by instruments on the surface or in orbit and provide distinctive information on near-surface planetary composition that is not accessible through any other phenomenology.

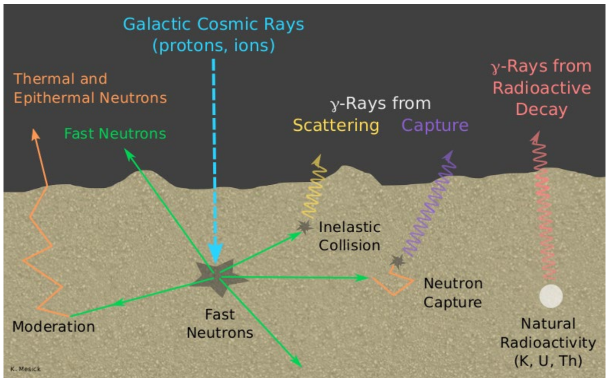

Figure 1: Cartoon illustrating the creation of GCR-induced neutrons and gamma rays from the surface of airless or near-airless planetary bodies.

These measurements are very difficult, requiring good gamma-ray energy resolution, neutron energy determination over twelve orders of magnitude, unraveling of the background cosmic radiation, and operation in the space environment under mission resource constraints. Some previous planetary missions that have included orbital neutron and/or gamma-ray spectroscopy instruments include Lunar Prospector[1], Kaguya[2], and LRO[3] to the Moon, Mars Odyssey[4] and Trace Gas Orbiter[5] to Mars, MESSENGER[6] to Mercury, and Dawn[7] to the asteroids Ceres and Vesta. Previous gamma-ray spectrometer instruments have ranged from scintillators like BGO with ~10% full-width half-maximum (FWHM) energy resolution at 662 keV to high-purity germanium (HPGe) with exquisite energy resolution but requiring cryo-cooling systems and frequent annealing. Previous neutron spectrometers have used ^{3}He tubes and/or ^{10}B-loaded plastic or ^{6}Li-glass scintillators, often with two identical detectors with one detector covered in Cd to block neutrons <0.4 eV thus providing two energy bins. The neutron and gamma-ray spectrometers provide complementary information and in the current generation of instrumentation are separate detectors that may share some components or electronics. Many of the planetary science NGRS built in the United States derive significant heritage from Los Alamos National Laboratory (LANL), which leverages national security expertise in space-based radiation detection.

The Elpasolite Planetary Ice and Composition Spectrometer (EPICS) instrument is an innovative low-resource NGRS with a fully integrated neutron and gamma-ray detector that incorporates two relatively new technologies to provide excellent neutron and gamma-ray detection efficiency and gamma-ray spectroscopy better than previous scintillator-based instruments with low size, weight, and power (SWaP) requirements. EPICS utilizes elpasolite scintillators which are sensitive to and can uniquely distinguish between neutrons and gamma rays within a single detection volume, combining what has previously been two separate instruments into one. Further reducing SWaP, EPICS utilizes silicon photomultipliers (SiPMs) that offer the high gain of traditional photomultiplier tubes (PMTs) at much smaller size, mass, and power. EPICS can provide significant value in performing elemental composition measurements and hydrogen mapping on planets and other small bodies from either an orbital or surface platform, in particular resource constrained missions.

EPICS INSTRUMENT

The EPICS instrument, shown in Figure 2, is under development at LANL and enabled by new scintillator and photodetector technologies. EPICS utilizes 1) elpasolite scintillators, which can be tailored to detect thermal, epithermal, and fast neutrons and gamma rays within the same detector volume and 2) SiPMs, which offer significant advantages over traditional photonics readout technology like PMTs. These technologies

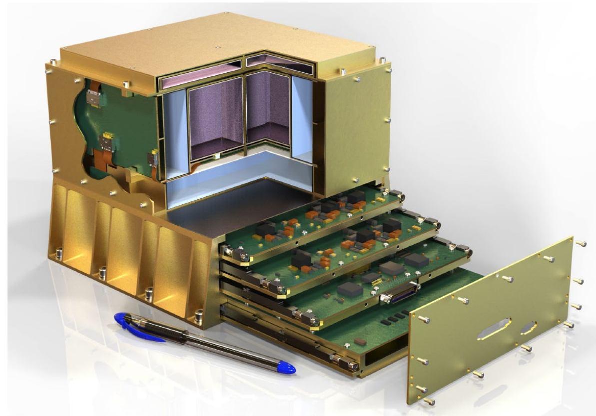

Figure 2: Rendering of the EPICS instrument.

combine to offer significantly reduced SWaP over previous NGRS instrumentation but with similar or improved performance. EPICS is a modular instrument that can be scaled to meet mission and performance requirements. Figure 2 features a 2x2 array of modules sized for orbital missions.

Elpasolite Scintillators

Elpasolites are a family of inorganic scintillators that are sensitive to both neutrons and gamma rays that can be uniquely distinguished through pulse-shape discrimination (PSD). Cerium-doped elpasolites produce a moderate light output between 20,000 and 60,000 photons/MeV with excellent linearity, yielding gamma-ray energy resolution as good 2.9% FWHM at 662 keV[8]. This is significantly better than previous scintillator-based NGRS instruments like BGO, NaI, CsI, which have energy-resolution between 6% - 10% at 662 keV. The most common, commercially available of the elpasolites is Cs_2LiYCl_6 (CLYC), which offers gamma-ray energy resolution as good as 4% at 662 keV, thermal neutron sensitivity through the ^{6}Li(n,α)T reaction, and some fast neutron sensitivity primarily through the ^{35}Cl(n,p)^{35}S reaction[9,10]. Elpasolites do not currently have space heritage, however, two space instruments utilizing CLYC scintillator are currently being built for flight: a LANL-developed instrument that will operate at geosynchronous Earth orbit[11] and the LunaH-Map CubeSat mission to the Moon[12], both scheduled to launch in 2021.

Typical scintillation light decay times, shown in Figure 3a for CLYC, are vastly different for incident neutron and gamma-ray radiation, allowing for robust pulse-shape discrimination by forming appropriate ratios of integrals over different regions of the pulse. For CLYC the optimized integration regions are the “prompt” (*P*) and “delayed” (*D*) regions, which correspond to the peak region and the tail regions of the pulse, respectively, as indicated in Figure 3a. A PSD ratio for

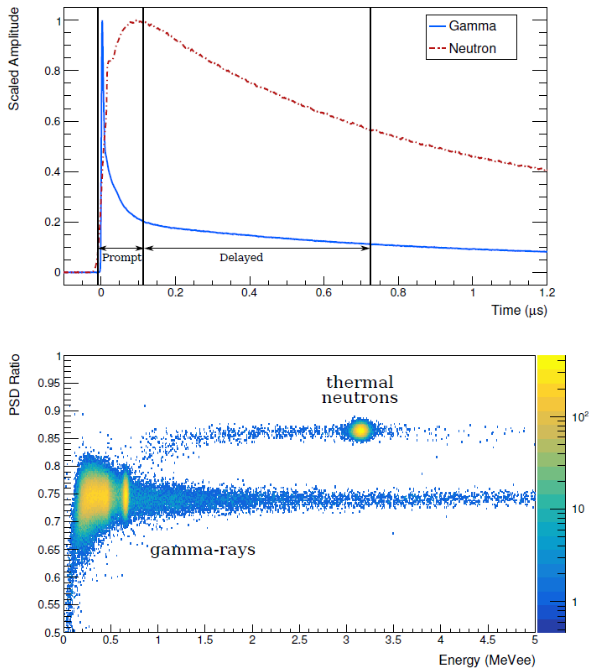

Figure 3: a) Typical pulse shapes from thermal neutron and gamma-ray radiation in CLYC; b) PSD ratio versus energy in CLYC demonstrating neutron-gamma discrimination.

CLYC is defined by the ratio *D/(P+D)* and a figure of merit (FOM) defined by taking the difference between the neutron and gamma-ray centroids in the PSD ratio divided by the sum of the FWHM of those peaks. Generally a FOM greater than 1 is desired, but the larger the FOM the better the neutron-gamma separation. Of the elpasolites, CLYC has the best discrimination between ^{6}Li-capture neutrons appearing around 3.2 MeV electron equivalent (MeVee) and gamma rays with a FOM of 4.55[13], as shown in Figure 3b. The band to the left of the ^{6}Li-capture peak are fast neutrons detected through the ^{35}Cl(n,p)^{36}S reaction.

Silicon Photomultipliers

Most commonly, scintillator-based radiation detectors use PMTs to convert the scintillation light produced by incident radiation into measureable electrical signals. SiPMs offer similar gain and noise performance to traditional PMTs, but are smaller, lighter weight, and require tens of volts of bias rather than kV-scale bias typical of PMTs. Newer SiPMs with good detection efficiency at blue wavelengths have shown excellent performance with elpasolites[14].

EPICS Instrument Design

The EPICS instrument baseline utilizes CLYC scintillator tiled with arrays of 6x6 mm^2 SiPMs for readout. As production of other elpasolite materials mature, CLYC can trivially be replaced by other elpasolites if their performance is more desirable. For example, CLLB and CLLBC provide the best energy resolution thus far of the elpasolites at 2.9%[8], but like all lanthanum-containing scintillators they exhibit low levels of internal alpha radioactivity that appear near the neutron band in PSD ratio[15,16]. TLYC is promising new elpasolite that replaces the Cs of CLYC with Tl, resulting in a higher effective Z and therefore improved gamma-ray stopping power[17]. However the thermal behavior of early TLYC samples at temperatures <0^{o}C require more study[18].

EPICS is designed to be a modular instrument, with a 2x2 array of modules shown in Figure 2 for an instrument optimized for orbital missions. A cutout cross section of a single module of the EPICS sensor assembly is shown in Figure 4 to better illustrate and describe the EPICS components. On the nadir surface (directed toward the planetary body, upwards in Figure 4) is a thin 0.6x5x5 cm^3 CLYC scintillator for detecting thermal neutrons. A Cd layer separates this front CLYC volume from a larger 5x5x5 cm^3 CLYC scintillator for detecting epithermal neutrons (>0.4 eV Cd cutoff) and gamma rays. The non-nadir faces of the large central CLYC volume can be surrounded by plastic scintillator to act as a veto for charged particle backgrounds as well as provide a fast neutron scatter signal that can be used in coincidence with a neutron capture in the central CLYC volume to detect fast neutrons. With supporting electronics, shielding, and packaging, the instrument in the 2x2 orbital configuration weighs approximately 7 kg and requires 14 W of power. This is approximately 45% less mass and 35% less power than that required by the MESSENGER NGRS[6] and 25% less mass and 8% less power than that required by the Dawn GRaND NGRS[7].

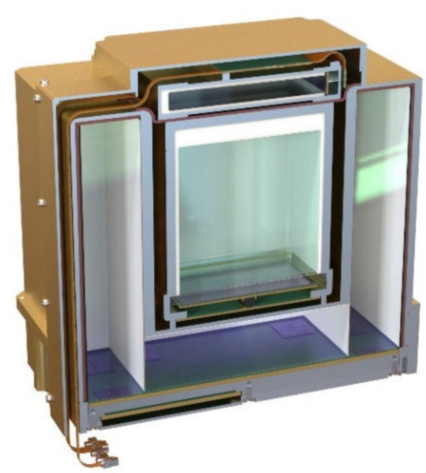

Figure 4: Cut-out of single module EPICS design.

EPICS is expected to operate within the temperature range -20°C to 50°C typically encountered in space, with performance of CLYC[19], CLYC readout with SiPMs[14], and gain stabilization algorithms[20] having already been demonstrated over this temperature range. We have also demonstrated sufficient radiation tolerance of CLYC and CLLBC[21] and the SensL J-series SiPMs utilized in EPICS[22] over the duration of a 10-year interplanetary mission. SensL J-series SiPMs also have space heritage from the U.S. Naval Research Laboratory's SIRI-1 mission[23].

EPICS Prototype Measurements

Components of a single EPICS module were procured and assembled into a laboratory prototype for performance measurements. Figure 5 shows the two CLYC elements of the prototype obtained from

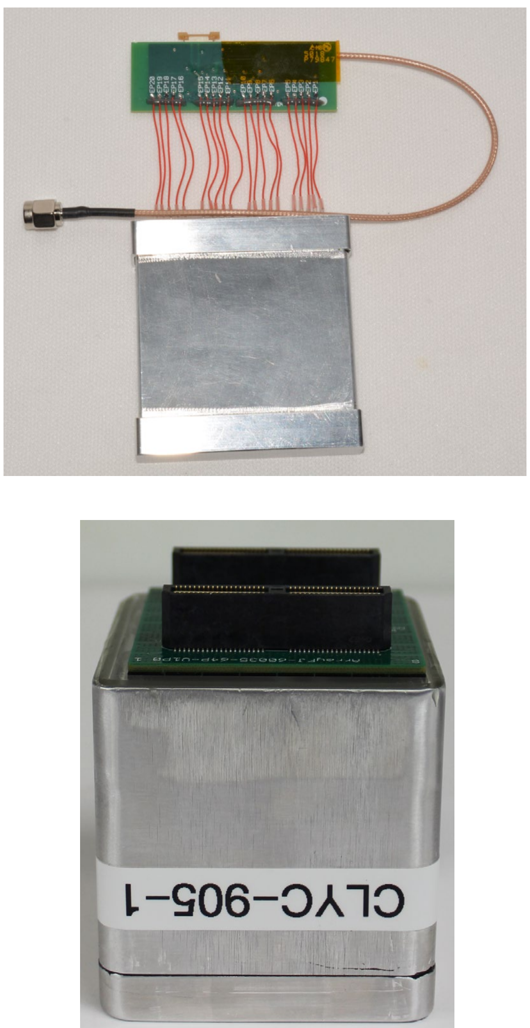

Figure 5: a) 0.6x5x5 cm^3 front CLYC module with encapsulated SiPM array; b) 5x5x5 cm^3 central CLYC module with 64-element SiPM array.

Radiation Monitoring Devices (RMD). The prototype elements were read out with 6x6 mm^2 ON Semiconductor (previously SensL) SiPM arrays tiled according to the geometry of each component. The thin CLYC module (Figure 8a) is read out by an 8-element SiPM array encapsulated in the CLYC packaging and the central CLYC module (Figure 8b) by a 64-element SiPM array attached with optical grease to a transparent quartz window.

Arrays of SiPMs like the 64-element array used in EPICS are required to read out large scintillator crystals. The primary challenge of using a large SiPM array to read out large scintillator crystals is preserving PSD performance when summing a large number of channels, which increases capacitance and destroys pulse shape information. As part of the EPICS design effort, our team optimized an amplification and summing circuit to read out the 64-element array of 6x6 mm^2 SiPMs, covering the 5x5x5 cm^3 CLYC crystal of the EPICS instrument design[24]. With four amplifiers and a single readout channel, the performance of this system was similar to energy resolution and PSD FOM measurements obtained with a 3" super-bialkali PMT. An energy resolution of 5.5% FWHM at 662 keV, shown in Figure 6a, and a PSD FOM of 3.6, shown in Figure 6b, were obtained. In addition, linearity up to 8 MeV and clean detection of the 7.6 MeV gamma ray iron doublet and associated single and double escape peaks, shown in Figure 7, were obtained.

The CLYC crystals with SiPM array readout shown in Figure 5 also demonstrate the compactness provided by utilizing SiPM readout. Compared to PMTs typically used to read out scintillators of this size, SiPMs represent a volume reduction of 70-90%[22].

Figure 8 shows the EPICS laboratory prototype partway through construction so certain elements can be observed. The central CLYC volume with the readout on the bottom side is surrounded by 3 plastic volumes. The plastic volumes are all read out by 2x2 SiPM arrays on the bottom of the instrument – 4 for each side plastic volume and 5 for the bottom plastic volume. The fully assembled EPICS prototype underwent preliminary performance characterization. This effort was largely focused on demonstrating system-level functionality and measuring key system properties. We demonstrated the ability to detect fast neutrons through a coincidence of the side plastic and central CLYC volume, and measured the characteristic time between the two pulses. The approach was similar to that used to characterize the fast neutron response of the Mars Odyssey Neutron Spectrometer[25], but for that instrument the fast scatter and subsequent neutron capture were within the same volume of ^{10}B-loaded plastic. We also calibrated the angular response of

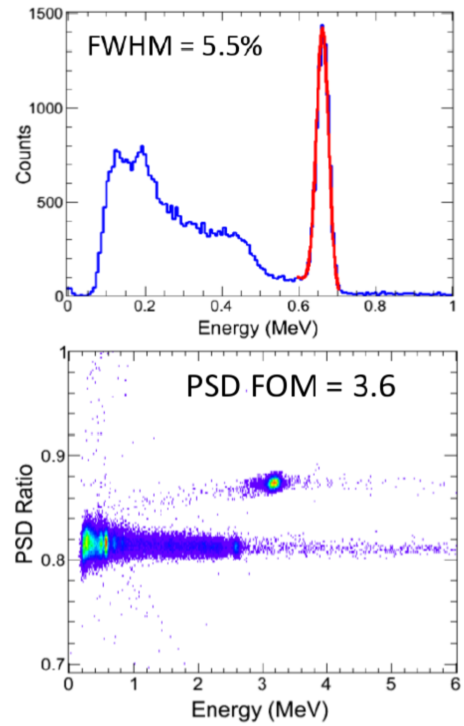

Figure 6: Measurements obtained with 5x5x5 cm^3 CLYC scintillator read out with 64-element SiPM array[24]. a) Gamma-ray energy spectrum from ^{137}Cs; b) PSD ratio showing neutron-gamma discrimination.

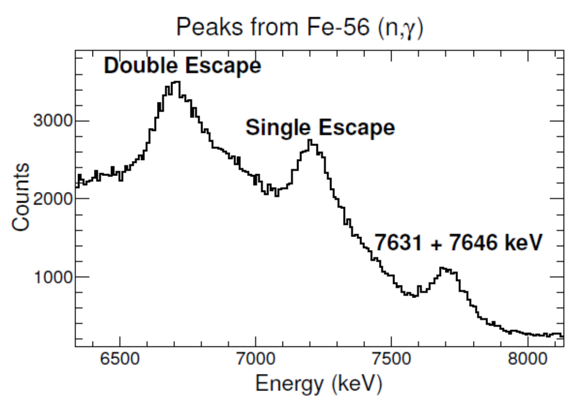

Figure 7: Gamma-ray spectrum measured by EPICS from neutron capture on iron near 7.6 MeV.

EPICS at LANL's Neutron Free In Air (NFIA) facility, which has been used to calibrate multiple previous or upcoming planetary NGRS instruments[1,7,12]. The NFIA consists of a large room with a suspended mezzanine where the instrument can be placed on a rotating table at precise distances from NIST-calibrated neutron sources. The mounting platform is far from the walls, floor, and ceiling to minimize "room return" effects on detected signals, which is of extreme importance for obtaining accurate neutron efficiency calibration.

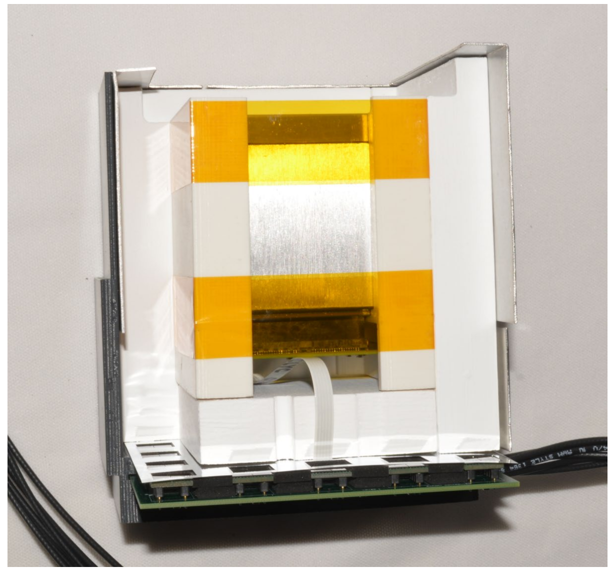

Figure 8: Picture of EPICS laboratory prototype partway through construction.

EPICS PERFORMANCE SIMULATIONS

The EPICS instrument is applicable to numerous potential rendezvous and landed missions to airless or near-airless bodies. The full size instrument (2x2 array of modules, shown in Figure 2) has been optimized for an orbital rendezvous with a small planetary body, such as an asteroid or moon. A smaller single module version is appropriately sized to provide high-resolution elemental mapping of the Moon or Mars from a low-orbit spacecraft, balloon, or other flying craft, or be used on a small lander or rover to assess resource utilization. We have performed simulations to estimate the instrument requirements and expected sensitivity and performance of EPICS in several notional missions. The GCR-induced neutron and gamma-ray return albedo was simulated using the radiation transport code MCNP6[26] and the instrument response simulated using the radiation transport code Geant4[27].

Asteroid Rendezvous

EPICS can be used to discriminate between compositional classes for a range of primitive bodies. An example of the utility of EPICS for geochemical composition measurements in shown in Figure 9. Figure 9a shows elemental ratios for Fe/Si versus Fe/O from a meteorite composition database[28], which demonstrate clear groupings for three different classes of asteroid compositions: carbonaceous chondrites, ordinary chondrites, and achondrites. Using EPICS to measure Fe, Si, and O gamma rays, a 2-week measurement at an orbital distance of 1 radius above the planetary surface allows percent-level statistical uncertainties to be achieved. This corresponds to the uncertainties shown in the ratios in Figure 9b for three simulated asteroid compositions within these classes.

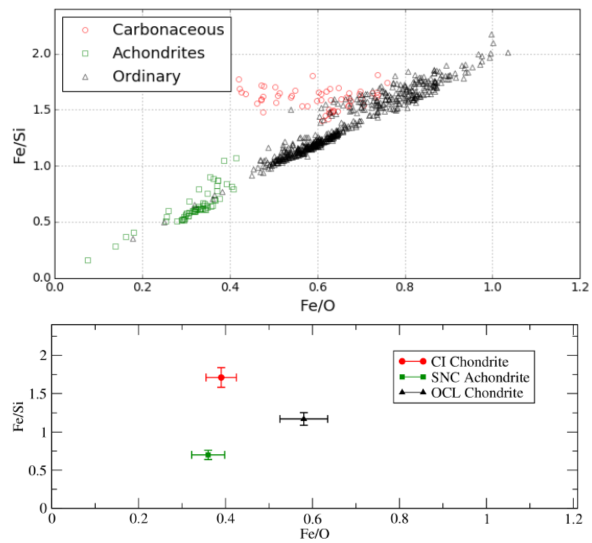

Figure 9: a) Elemental ratios Fe/Si versus Fe/O from meteorite composition database[28] showing discrimination between three groups of asteroid compositions; b) Simulated uncertainties from a 2 week EPICS measurement of these ratios.

The detection of neutrons by EPICS is a key tool for studying the abundance of water on primitive bodies, in particular water that may be present beneath the surface and accessible to sample return or drilling missions. EPICS can discriminate between low (10s of ppm) and high (percent level) amounts of H rapidly, in 12-24 hours in orbit. In addition, with the detection of neutrons from three energy bands (thermal, epithermal, and fast), layering of water within the near-surface can be determined, as illustrated in analysis of Mar Odyssey neutron data[29].

Martian Moons

There are three main hypotheses for how the martian moons Phobos and Deimos were formed: Hy1) in-situ accretion from giant impact ejecta, Hy2) co-accretion from the proto-martian disk; and Hy3) capture of a primitive asteroid or extinct comet. Determining how Phobos and Deimos were formed can provide important information about the formation and early history in the boundary region between the inner and outer solar system. The abundances of elements H, Si, K, Fe, Th, and U can be used to distinguish between the three origin hypotheses. Elemental compositions representative of these hypotheses were simulated. Figure's 10 and 11 show the GCR-induced neutron and gamma-ray return albedo, respectively, at an orbital distance of 2 radii above the moon's surface. The difference in hydrogen abundances between the three origin hypothesis compositions leads to significant differences in the expected neutron flux spectrum.

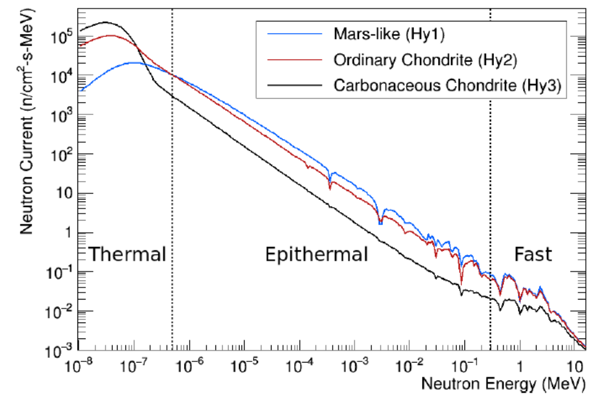

Figure 10: The simulated neutron albedo spectrum from Phobos or Deimos assuming elemental compositions relevant to the three origin hypotheses.

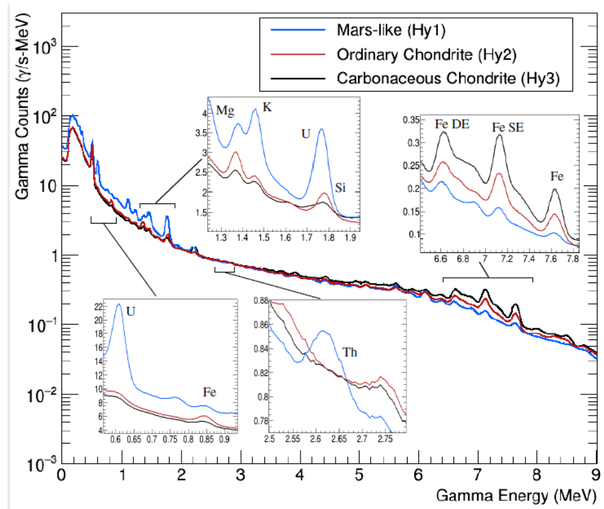

Figure 11: Simulated as-measured gamma-ray spectrum from Phobos or Deimos assuming elemental compositions relevant to the three origin hypotheses.

EPICS can distinguish between the neutron signals in less than an Earth day in orbit at 2 radii above the surface or with several fly-by's with a closet approach of 1 radius above the surface. The simulated gamma-ray spectrum as measured by EPICS assumes a 6% FWHM energy resolution, easily achievable given prototype performance measurements, and insets in the figure indicate gamma-ray lines for key elements that could be used to distinguish between the three origin hypotheses within a few days in orbit.

Lunar Lander

On a landed or roving lunar mission, a single module EPICS instrument could rapidly detect and quantify hydrogen abundance and measure elemental abundances relevant to classifying rock types and in-situ resource utilization potential. Using GCR-induced neutron and gamma-ray return albedo on the surface, EPICS can provide measurements to distinguish between major rock types on the Moon in just a few hours and measure H enrichments down to 30 ppm within 6 hours. Increased sensitivity and better statistical uncertainties are provided in longer measurements, but the short measurement time means EPICS can provide information on a relatively mobile platform.

Figure 12 shows the FeO and MgO elemental composition of major lunar material types and the modeled composition from a 12-hour EPICS measurement, demonstrating the ability of EPICS to distinguish between the various groups with good statistical uncertainty. The colored circles in this plot represent the average and standard deviation over multiple measurements in each category of Apollo sample types[30].

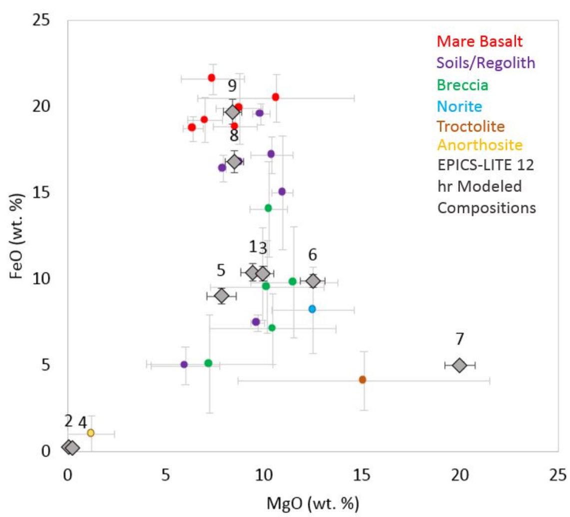

Figure 12: FeO versus MgO for several classes of lunar material, with colored circles representing measurements in each category of Apollo samples and grey diamonds representing 12-hour EPICS measurements from a landed or roving platform.

SUMMARY

The EPICS instrument is an innovative, low-resource neutron and gamma-ray spectrometer that utilizes elpasolite scintillators for combined neutron and gamma-ray detection and silicon photomultipliers for readout. Neutrons and gamma-rays are produced by the interaction of galactic cosmic rays in the near-surface of planetary bodies and provide unique signatures of elemental composition. EPICS has the ability to answer important planetary science questions related to understanding the role of primitive bodies as building blocks for planets and life. The EPICS instrument has the ability to robustly determine elemental composition and hydrogen content and layering to depths of tens of centimeters in planetary surfaces from orbiting, flying, landed, or roving platforms. The low-resource nature of the EPICS instrument makes it beneficial to many future planetary science missions including investigations of asteroids, satellites, and other primitive bodies, as well as improved spatial resolution mapping of hydrogen and other elements on the Moon or Mars, and resource identification for future human exploration and the Moon and Mars.

Acknowledgements

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References

1. Feldman, W.C et al, “Gamma-Ray, Neutron, and Alpha-Particle Spectrometers for the Lunar Prospector mission,” Journal of Geophysics Research: Planets, vol. 109, No. E07S06, 2004.
2. Kobayashi, K. et al, “The Kaguya gamma-ray spectrometer: instrumentation and in-flight performances,” Journal of Instrumentation, vol. 8, No. 4, 2013.
3. Mitrofanov, I.G. et al, “Lunar Exploration Neutron Detector for the NASA Lunar Reconnaissance Orbiter,” Space Science Reviews, vol. 150, No. 1, 2010.
4. Boynton, W.V. et al, “The Mars Odyssey Gamma-Ray Spectrometer Instrument Suite,” Space Science Reviews, vol. 110, No. 1, 2004.
5. Mitrofanov, I.G. et al, “Fine Resolution Epithermal Neutron Detector (FREND) Onboard the ExoMars Trace Gas Orbiter,” Space Science Reviews, vol. 214, No. 86, 2018.
6. Goldsten, J.O. et al, “The MESSENGER Gamma-Ray and Neutron Spectrometer,” Space Science Reviews, vol. 131, No. 1, 2007.

7. Prettyman, T.H. et al, "Dawn's Gamma Ray and Neutron Spectrometer," Space Science Reviews, vol. 163, No. 1, 2011.
8. Glodo, J. et al, "Selected Properties of Cs_2LiYCl_6, $Cs_2LiLaCl_6$, and $Cs_2LiLaBr_6$ Scintillators," IEEE Transactions on Nuclear Science, vol. 58, No. 1, 2011.
9. Glodo, J. et al, "Fast Neutron Detection with Cs_2LiYCl_6," IEEE Transactions on Nuclear Science, vol. 60, No. 2, 2013.
10. Smith, M.B. et al, "Fast neutron measurements using Cs_2LiYCl_6:Ce (CLYC) scintillator," Nuclear Instruments and Methods in Physics Research Section A, vol. 784, 2015.
11. Coupland, D.D.S, et al, "The SENSER CLYC Experiment," in 2016 IEEE Nuclear Science Symposium and Medical Imaging Conference proceedings, 2016.
12. Hardgrove, C. et al, "The Lunar Polar Hydrogen Mapper CubeSat Mission," IEEE Aerospace and Electronic Systems Magazine, vol. 35, No. 3, 2020.
13. Lee, D.W. et al, "Pulse-shape analysis of Cs_2LiYCl_6:Ce scintillator for neutron and gamma-ray discrimination," Nuclear Instruments and Methods in Physics Research Section A, vol. 614, 2012.
14. Mesick, K.E. et al, "Performance of several solid state photomultipliers with CLYC scintillator," in 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference proceedings, 2015.
15. Mesick, K.E. et al, "Pulse-shape discrimination and energy quenching of alpha particles in $Cs_2LiLaBr_6:Ce^{3+}$," Nuclear Instruments and Methods in Physics Research Section A, vol. 841, 2017.
16. Woolf, R.S. et al, "Characterization of the internal background for thermal and fast neutron detection with CLLB," Nuclear Instruments and Methods in Physics Research Section A, vol. 838, 2016.
17. Hawrami, R. et al, "Tl2LiYCl6: Large Diameter, High Performance Dual Mode Scintillator," Crystal Growth & Design, vol. 17, No. 7, 2017.
18. Watts, M.M. et al, "Thermal Characterization of Tl_2LiYCl_6:Ce (TLYC)," IEEE Transactions on Nuclear Science, vol. 67, No. 3, 2020.
19. Budden, B.S. et al, "Characterization and Investigation of the thermal dependence of $Cs_2LiYCl_6:Ce^{3+}$ (CLYC) Waveforms," IEEE Transactions on Nuclear Science, vol. 60, No. 2, 2012.
20. Budden, B.S. et al, "Gain stabilization and pulse-shape discrimination in a thermally-variant environment for a handheld radiation monitoring device utilizing $Cs_2LiYCl_6:Ce^{3+}$ (CLYC) scintillator," in IEEE Nuclear Science Symposium and Medical Imaging Conference proceedings, 2012.
21. Mesick, K.E. et al, "Effects of proton-induced radiation damage on CLYC and CLLBC performance," Nuclear Instruments and Methods in Physics Research Section A, vol. 948, 2019.
22. Bartlett, K.D. et al, "Proton irradiation damage and annealing effects in ON Semiconductor J-series silicon photomultipliers," Nuclear Instruments and Methods in Physics Section A, vol. 969, 2020.
23. Mitchell, L.J. et al, "Radiation damage assessment of SensL SiPMs," Nuclear and Space Radiation Effects Conference Paper, 2020.
24. West, S.T. et al, "Compact readout of large CLYC scintillators with silicon photomultiplier arrays," Nuclear Instruments and Methods in Physics Research Section A, vol. 951, 2020.
25. Feldman, W.C. et al, "Fast neutron flux spectrum aboard Mars Odyssey during cruise," Journal of Geophysical Research: Space Physics, vol. 107, 2002.
26. Werner, C. editor, "MCNP User Manual – Code Version 6.2," Los Alamos National Laboratory Report LA-UR-17-29981, 2017.
27. Agostinelli, S. et al, "Geant4: A simulation toolkit," Nuclear Instruments and Methods in Physics Research Section A, vol. 506, 2003.
28. Nitler, L.R. et al, "Bulk element composition of meteorites: A guide for interpreting remote sensing geochemical measurements of planets and asteroids," Antarctic Meteorite Research, vol. 17, 2004.
29. Pathare, A.V., "Drive by excess? Climatic implications of new global mapping of near-surface water-equivalent hydrogen on Mars," Icarus, vol. 301, 2018.
30. Taylor, G.J. et al, "Lunar Minerals," in Lunar Sourcebook: A User's Guide to the Moon, 1991.