NUCLEAR SPECTROSCOPY OF ASTEROID 16 PSYCHE.

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Introduction: NASA's recently selected Psyche mission will investigate 16 Psyche, an M-type asteroid thought to be the exposed core of a now-disrupted protoplanet [1]. Psyche's payload includes a Gamma-Ray and Neutron Spectrometer (GRNS) to characterize the elemental composition of 16 Psyche from orbit. Psyche GRNS has stated goals of mapping the metal-to-silicate ratio across Psyche's surface, mapping Ni and Fe content, and measuring the average Si, K, S, Al, Ca, Th, and U content of the surface. The Psyche GRNS may also measure other elements, including C, P, and Co, depending on Psyche's composition, the in-flight performance of the instrument, and the implenented mission operations plan.

Psyche is a unique object and prior nuclear spectroscopy experience may mislead interpretation of Psyche GRNS datasets. Previous investigations have been of worlds made of rock and/or ice (Moon, Mercury, Mars, asteroids 433 Eros, 4 Vesta, 1 Ceres); nuclear processes will be sufficiently different on a metal-dominated world that detailed modeling and measurements of Psyche-specific scenarios are needed. Examples are given below, and are based on a notional model of 16 Psyche's surface composition as 90% metal (>4 wt% Ni, remainder Fe) and 10% Mg-rich orthopyroxene, as suggested by radar [2], spectral [3], and meteorite studies.

Fast Neutron Signatures: Galactic cosmic rays (GCR) bombard the surfaces of airless worlds, liberating neutrons from atomic nuclei during nuclear spallation. The liberated neutrons have energies of ~1 to ~10's of MeV (termed "Fast Neutrons"). *Gasnault et al.* [4] discovered a linear relationship between fast-neutron production and the average atomic mass (<A>) of materials on the Moon, a relationship that has been extended to analysis of data from Mercury and 4 Vesta.

The surfaces of silicate bodies are composed of a wide variety of elements, including O, Mg, Al, Si, Ca, Ti, and Fe. Psyche's surface is likely dominated by just two elements: Fe (A=55.8) and Ni (A=58.7). Under the lunar paradigm, an increase in fast neutron count rates would be interpreted as an increase in <A>, and thus an increase in Ni. Yet radiation transport models show the opposite effect for Psyche – adding Ni to an Fe-dominated composition lowers fast neutron count rates.

Our hypothesis is that Ni suppresses fast neutron production due to its higher neutron separation energy (12.2 MeV for ^{58}Ni) relative to Fe (11.1 MeV for ^{56}Fe). Additionally, the most common Ni isotope (^{58}Ni; 68%) has the same number of neutrons (30) as the most common Fe isotope (^{56}Fe; 92%), so the neutrons per unit <A> available for spallation is relatively constant when Ni is added to Fe. The result of these two effects is that the number of neutrons liberated per GCR on Psyche decreases with increasing Ni content, and by extension increasing <A>.

Thermal Neutron Absorption: Epithermal (0.2 eV < energy < 0.5 MeV) and thermal (energy < 0.2 eV) neutrons are produced via downscattering of GCR-produced fast neutrons within near-surface materials. Thermal neutrons can be absorbed by elements with high neutron-absorption cross sections (σ_a), for instance Fe, Ti, Ni, Mn, Cr. Thermal neutron measurements can be used to map absorption-dependent composition, specifically the macroscopic neutron absorption cross section (Σ_a) of Psyche's surface materials. If Psyche is made almost entirely of elements with high σ_a (Fe, Ni), our models show that Psyche will emit exceptionally low thermal neutron emissions. A GRNS-resolved patch of silicate-rich material would appear as a distinct source of thermal neutrons, making thermal neutron measurements a sensitive indicator of Psyche's metal-to-silicate distribution.

For the Moon, Fe and Ti were detrended from lunar thermal neutron measurements to infer the concentrations of rare-Earth elements (REE) with high σ_a [5]. The detrended neutron data were converted to maps of Gd and Sm concentrations, REEs that are present in lunar KREEP-enriched materials. A similar analysis may be possible on Psyche. Iron meteorites have Co concentrations of ~0.4–0.8 wt% and wide-ranging Ir concentrations of ~6 ppb up to nearly ~0.01 wt%. The σ_a values for these elements (37.2 mb, 422.91 mb) are an order of magnitude or more higher than Fe (σ_a=2.5 mb) and Ni (σ_a=4.39). Following [5], Co and Ir concentrations might be derived from residual (Fe- and Ni-detrended) thermal neutron data if the concentrations are high enough on Psyche. Co and Ir are highly siderophoile elements, so any constraints on their abundance from GRNS measurements will be useful for charascterizing Psyche's formation.

Radionuclide Production: GCR-induced reactions modify the isotopic composition of extraterrestrial materials, including Psyche's surface. This process can generate radioactive elements that are detectable by GRNS. Our radiation transport models show that radionuclide production is negligible for silicates but is significant for metals. We tested the validity of these models, and the implications for Psyche GRNS measurements, with a meteorite irradiation experiment. We irradiated a Psyche surface analog – a 10 cm x 10 cm x 1.5 cm block of the iron meteorite Campo del Cielo – with 1 GeV protons at the Brookhaven National Laboratory's (BNLs) NASA Space Radiation Laboratory. 1 GeV protons are near the mean energy of GCRs, and we gave the meteorite a dose equivalent to the number of GCR protons seen at the surface during an ~80 year period.

Prior to irradiation, the meteorite showed no evidence of radioactivity. After the irradiation, the meteorite was emitting gamma rays at ~100 distinct energies, including from the radioactive elements: ^{7}Be ($t_{1/2}$=53.22 d), ^{27}Mg ($t_{1/2}$=9.5 m), ^{29}Al ($t_{1/2}$=6.6 m), ^{34}C[146.3 keV] ($t_{1/2}$=31.99 m), ^{37}S ($t_{1/2}$=5.1 m), ^{39}Cl ($t_{1/2}$=55.6 m), ^{41}Ar ($t_{1/2}$=109 m), ^{43}Sc ($t_{1/2}$=3.891 h), ^{44}Sc ($t_{1/2}$=58.61 m), ^{46}Sc ($t_{1/2}$=83.79 d), ^{47}Sc ($t_{1/2}$=3.35 d), ^{48}Sc ($t_{1/2}$=43.67 h), ^{48}V ($t_{1/2}$=15.97 d), ^{48}Cr ($t_{1/2}$=21.56 hr), ^{49}Cr ($t_{1/2}$=42 m), ^{51}Cr ($t_{1/2}$=27.7 d), ^{52}Mn ($t_{1/2}$=21 m; 5.6 d), ^{52}Cr ($t_{1/2}$=5.591 d), ^{53}Fe ($t_{1/2}$=2.54 m), ^{54}Mn ($t_{1/2}$=5.591 d), ^{56}Co ($t_{1/2}$=77.236 d), ^{56}Mn ($t_{1/2}$=2.58 hr), ^{57}Co ($t_{1/2}$=271.74 d), ^{58}Co ($t_{1/2}$=70.86 d), and ^{60}Co ($t_{1/2}$=1925.3 d). Each of these radionuclidies produces gamma rays that will be present during the GRNS measurements of Psyche's surface. Two examples are provided below.

Example #1: radionuclides as a background to Psyche GRNS measurements: During irradiation, ^{56}Co was produced via spallation of Ni (e.g. the ^{60}Ni(p,p′p3n)^{56}Co and ^{62}Ni(p, p′p5n)^{56}Co reactions). Three weeks after irradiation, the meteorite was emitting 846-keV gamma rays, which we attribute to decay of excited ^{56}Fe produced via ^{56}Co decay. This decay is a background to the prompt 846-keV gamma ray produced by (fast) neutron inelastic scattering on ^{56}Fe. Any attempt to use the 846-keV gamma-ray for Fe mapping must remove this ^{56}Co contribution.

Example #2: radionuclides as a new measurement opportunities: The same post-irradiation measurement also revealed a 810-keV gamma-ray peak, attributed to ^{58}Co decay. GCR-induced spallation only produces elements with lower mass and atomic number than the parent nucleus, so the ^{58}Co we observed was likely produced from spallation of Ni in the meteorite (e.g. the ^{60}Ni(p,p′pn)^{58}Co and ^{62}Ni(p,p′p3n)^{58}Co reactions). Thus, 810-keV gamma rays could provide a new mechanism for measuring Psyche's Ni content, beyond the planned measurement of prompt Ni (1454 keV) gamma rays from neutron inelastic scattering. Such a measurement requires knowledge of the relative reaction rates and the GCR flux at Psyche.

Considerations for Gamma-Ray Signatures: GCR-liberated neutrons produce prompt gamma rays in near-surface materials via neutron inelastic scattering and neutron capture reactions. The gamma rays that escape into space are produced within ~45 g/cm^2 of the surface. For a typical (e.g. rocky) surface material with density ~1.5 g/cm^3, 45 g/cm^2 corresponds to a depth of ~30 cm. If Psyche's surface is non-porous metal with a density as high as 8 g/cm^3 [2, 3], the sampling depth of the GRNS measurements be as little as ~6 cm.

Although our sensitivity varies by element and spacecraft altitude, measurements with a Psyche-GRNS-like instrument (e.g. [6]) are typically sensitive to elements with concentrations of ≥0.5 wt%. Exceptions are radioactive elements (K, Th, U), which can be measured at concentrations of ~10 ppb or higher. Gamma rays are isotope specific, but a single isotope usually dominates gamma-ray emission for a given element so GRNS measurements are reported as element, not isotope, measurements. Psyche may present an exception to this rule. If Psyche is ~85 wt% Fe with terrestrial Fe isotopic abundances (5.854% ^{54}Fe, 91.754% ^{56}Fe, 2.119% ^{57}Fe, and 0.282% ^{58}Fe), then these isotopes would be present at levels detectable by the Psyche GRNS with ~10-20% precision.

Psyche GRNS Status: The Psyche GRNS team is performing tests with an early prototype instrument with the goal of achieving laboratory quality measurements of Psyche from orbit. Modeling efforts are underway to characterize gamma-ray signatures for elements included in the Psyche mission requirements (e.g. Ni, Fe), as well as elements and signatures not considered during Psyche mission formulation (e.g. Co, P, C; high-energy gamma rays [7]). Measurements of Co/Ni may facilitate comparisons of Psyche with Fe meteorite types [8] defined from chemical data measured in the laboratory. We are also studying the impact that variable (~100 ppm) concentrations of H [9] will have on our measurements. Finally, we are developing a robust set of possible Psyche compositions using the latest publications [2, 3, 9, 10, 11] for use in ongoing sensitivity studies.

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