

# Understanding the nuclear emissions from metal bodies through experiment: Preparation for the Psyche Mission to a metal world

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Basalt

Odessa IAB

Sericho Pallasite

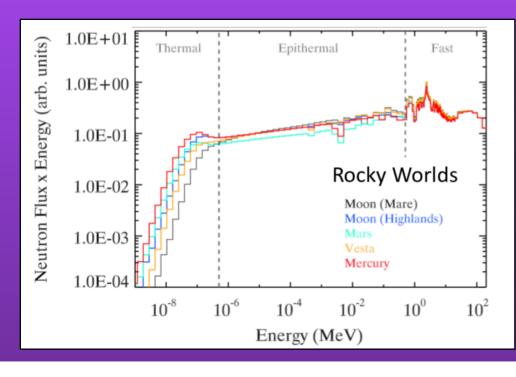
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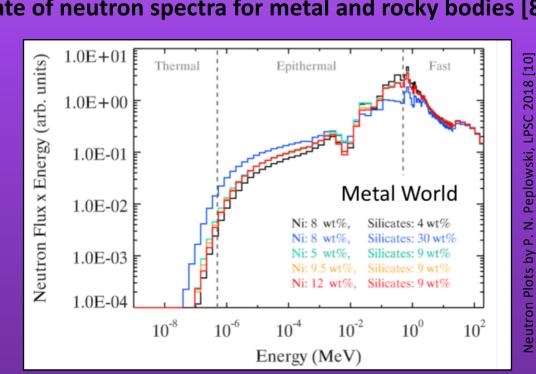
## Introduction & Background

Gamma-ray spectroscopy can be used to determine planetary elemental compositions, providing key information for understanding planet formation and evolution. Orbital gamma-ray measurements have been collected previously from rocky or icy bodies such as Mercury, the Moon, (1) Ceres, (4) Vesta, (433) Eros, and Mars [1-6]. However, we have never visited an all-metal body. Asteroid (16) Psyche is likely dominated by iron-nickel metal [7]: as a result its bulk neutron cross section and resulting nuclear processes should be significantly different from that of the well-studied rocky bodies [8, 10]. This research is being done in order to build an experimentally verified, comprehensive database of possible Psyche gamma-ray emissions and to have a better understanding of the data that will be collected during the mission and what these data may imply about the formation of (16) Psyche.

#### Nuclear Interactions with Metal

High energy galactic cosmic rays (GCRs) penetrate the surface of solar system objects that have little or no atmosphere. GCRs liberate neutrons from nuclei within the surface material in a process called spallation; these liberated neutrons then continue to interact with other nuclei, resulting in downscattering of neutrons and the emission of gamma-rays. (16) Psyche's composition is expected to be dominated by metal (Fe, Ni), such that nuclear processes on its' surface are expected to be substantially different than that of rocky bodies. Both Fe and Ni have relatively high neutron-absorption cross sections, resulting in fewer thermal neutrons due to this absorption. The nuclear environment on Psyche is therefore likely dominated by fast and epithermal neutrons, the plots below show estimate of neutron spectra for metal and rocky bodies [8, 10].





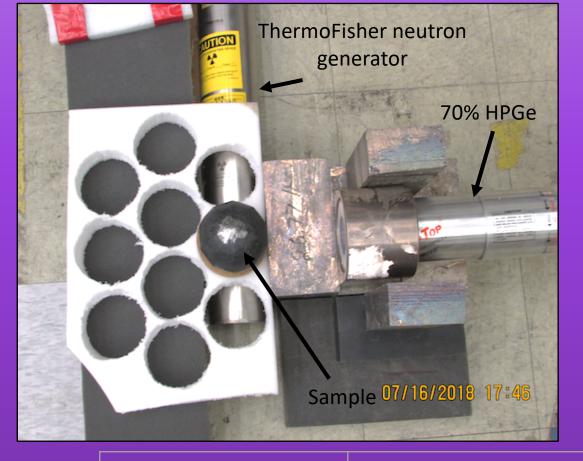
## Samples

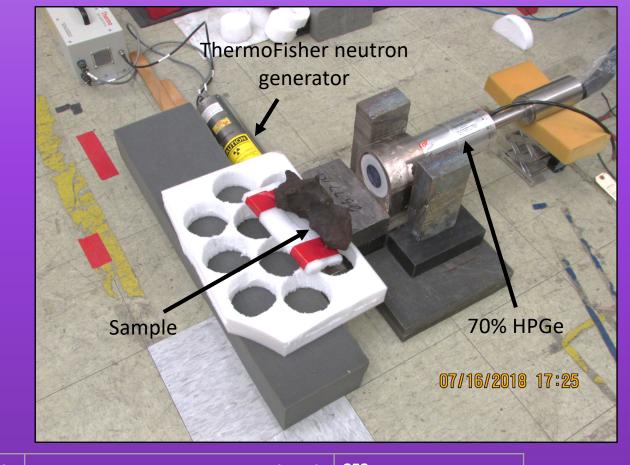
For these experiments, we chose to test samples that represent some of the science requirements for the Psyche Discovery mission. The gamma-ray spectrometer will measure and map the abundances of nine key elements (Fe, Ni, Si, K, S, Al, Ca, Th, U) on (16) Psyche. Our samples consist of materials with high amounts of five of these elements (Fe, Ni, Si, Al, S). Two meteorites, an Odessa (IAB-MG) iron sample and a Sericho pallasite sample were also used in these experiments to represent core-like material and core-mantle mixture material, respectively. Historically, neutron activation studies of meteorites used samples that were highly processed (cut, etched, thinned, shaped, etc.) to achieve high-precision composition measurements [9]. In order to study the possible gamma-ray signatures at (16) Psyche, we intentionally used bulky, unprocessed materials to more closely mimic the imperfect geologic conditions that may be encountered during the mission.

Sample	Approximate Composition	<b>Expected Gamma-Ray Lines</b>	Geologic Relevance			
Odessa (iron IAB-MG)	7.35 wt% Ni, 0.48wt% Co, 0.25 wt% P, 0.50 wt% S, 0.2 wt% C, 75 ppm Ga, 285 ppm Ge, 2 ppm Ir [12]	Fe (847keV, 1408keV), Ni (1332keV, 1454keV, 9MeV), Mg (1369keV, 1809keV), Co (1332keV, 1173keV)	Core material analog (iron, nickel) containing small amounts of cobalt, sulfur, and phosphorous; sulfur cabe found in inhomogenously distributed triolite noduthat likely represent melt trapped during crystallization			
Sericho (pallasite)	12.3 wt% Olivine (Fa), FeO/MnO 57.4, Cr <sub>2</sub> O <sub>3</sub> 0.03 wt%, 7.1 wt% Kamacite Ni, 0.81 wt% Co, 0.06 wt% P, Schreibersite [13]; ~ 29 wt% Fe, 4-5 wt% Ni, 3-6 wt% S, 16 wt% Mg, 13 wt% Si, 29 wt% O [14, 15]	Fe (847keV, 1408keV), Ni (1332keV, 1454keV), Mg (1369keV, 1809keV), Si (1779keV), S (2232keV)	Core-mantle boundary material analog containing large amounts of high-Mg olivine, sulfur, and nickel; lighter elements (Si, O, S) mixed with heavier elements (Fe, Ni measurements from reflectance spectra indicate Psyche's surface is ~10% silicates			
Basaltic andesite (Pinacate volcanic field)	~ 24 wt% Si, 6 wt% Al, 7 wt% Fe, 4 wt% Mg, 6 wt% Ca, 3 wt% Na, 1 wt% K, 0.8 wt% Ti, 45+ wt% O [16]	Si (1779keV), Mg (1369keV, 1809keV), Fe (847keV, 1408keV), Ca (1942keV), Na (440keV), Al (844keV, 1014keV, 2211keV)	High-silicate terrestrial comparison sample, possible analog for primitive chondritic in-fall material from impacts, much like the black layers found on (4) Vesta			
Iron pyrite (rocks)	FeS <sub>2</sub> ; ~53 wt% S, ~47 wt% Fe	Fe (847keV, 1408keV), S (2232keV)	Sulfur-rich iron material, may be deposited back atop Psyche's surface or excavated by impacts; important for understanding sequestration of light elements into planetary cores			
6061 Aluminum (disk)	95 wt% Al, 0.5 wt% Si, 0.7 wt% Fe, 0.4 wt% Cu, 1.2 wt% Mg, 0.35 wt% Cr, other elements <0.15 wt% (ASTM standard)	Al (844keV, 1014keV, 2211keV)	"Pure" substance; important for crystallization in metallic melts & mantle formation, also a spacecraft background analog material			
1020 Steel ("iron ball")	99 wt% Fe, 0.6 wt% C, 0.4 wt% Mn (ASTM standard)	Fe (847keV, 1408keV)	"Pure" substance for isolating other sample signals & comparison with Ni-poor samples			
Nickel (bars)	Unknown purity, assumed 99 wt% Ni	Ni (1332keV, 1454keV, 9MeV)	"Pure" substances; important for understanding trace			
Cobalt (bars)	99% Co purity	Co (1332keV, 1173keV)	element partitioning and sequestration of light element into planetary cores, and how materials crystallize within			
Sulfur (powder)	99.9% S purity	S (2232keV)	metallic melts			
	08/18	S6409°	08/13/2¢			
4.4kg 1020 Steel 3.3kg Sericho			0.58kg 0.9kg Iron			

## Experiment

Experiments were performed at Lawrence Livermore National Laboratory in a former nuclear reactor building that contains a low-mass aluminum scaffolding floor, allowing for "free in air" measurements. A 70% efficiency high-purity germanium (HPGe) gamma-ray spectrometer was used with <sup>3</sup>He and a stilbene detector. Data was collected using a Canberra Lynx acquisition system and analyzed using Python. **The experimental set-up is shown in the images below.** The HPGe detector was surrounded by bismuth and borated polyethylene in order to minimize fast neutron interactions within the detector material.





<b>Neutron Source</b>	Deuterium-Tritium (DT)	Deuterium-Deuterium (DD)	<sup>252</sup> Cf Source
Energy	14.1 MeV	2.45 MeV	1-2 MeV
Neutrons per Second	10 <sup>6</sup> - 10 <sup>8</sup>	10 <sup>5</sup> - 10 <sup>7</sup>	10 <sup>5</sup>

# 500

Iron and Nickel

DD Neutron Generator Source Spectra

Since rocky bodies have more thermal neutrons than metal-rich bodies, gamma rays resulting from thermal-neutron capture are often used to determine elemental composition on such bodies [1-6, 17]. In contrast, Psyche's expected metal-rich environment may allow for more prompt gamma-ray emissions due to higher-energy neutron inelastic scattering. We investigated the prompt 1408 keV <sup>54</sup>Fe gamma ray and compared it to the <sup>58</sup>Ni 1454 keV gamma ray.

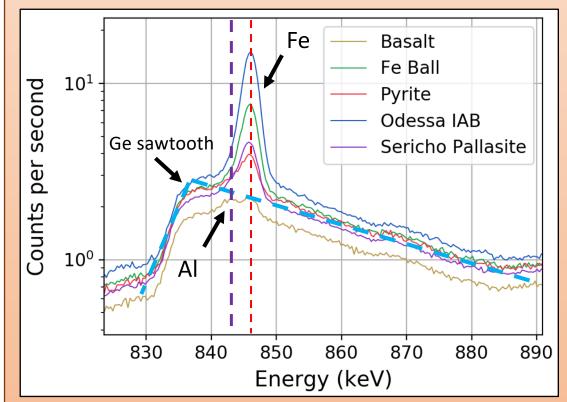
1) Similar energies

Interferences

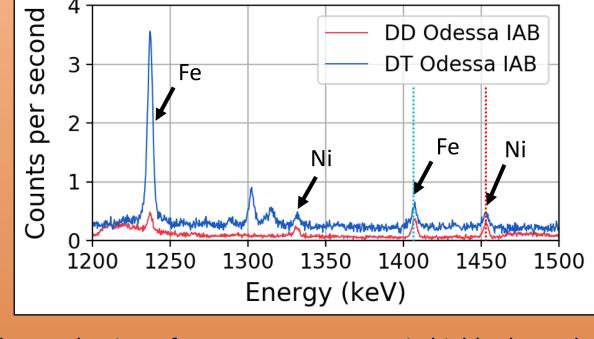
c) Similar absorption

forming elements

background interferences



The Fe(n,n'g) 847 keV capture line is shown above with several other competing gamma-ray lines. The curve at 834 keV labeled sawtooth is due to fast neutrons interacting in the HPGe detector. The other peaks in the spectra are from the decay of <sup>54</sup>Mn, and possibly some S(n,g), at 841 keV, from Al(n,n'g) at 844 keV, and from the decay of <sup>56</sup>Co at 854 keV [11].



Jsing the production cross sections ( $\sigma$ ), natural abundances ( $\varepsilon$ ), and

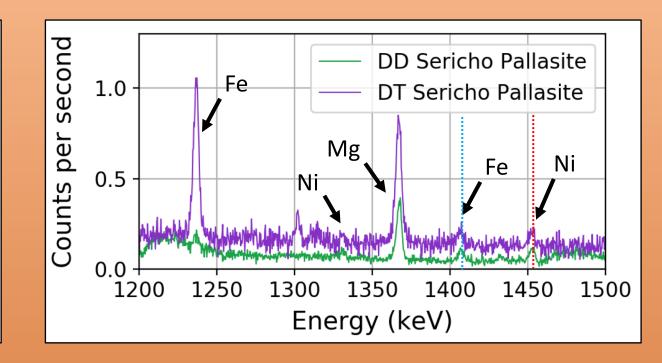


Table 2: Fe/Ni Ratios for Meteorite Samples

1) No significant interferences found from major rock-

4) Solar particle events, <sup>54</sup>Fe + p  $\rightarrow$  <sup>55</sup>Co +  $\gamma \rightarrow$  <sup>55</sup>Co  $\rightarrow$ 

<sup>55</sup>Fe +  $\gamma$  (t<sub>1/2</sub> = 17.5 hrs), advantageous compared to

the 847 keV line proton interaction ( $t_{1/2} = 77$  days)

3) <sup>111</sup>Cd line at 1410.5 keV (shielding on <sup>3</sup>He tube)

1000

Advantages of 1408 keV/1454 keV

a) Detector efficiencies are relatively equal

b) Background signals are relatively equal

2) Fewer similar-energy gamma-ray lines or

2) <sup>27</sup>Al line at 1408.3 keV (thermal capture)

The production of prompt gamma-rays is highly dependent upon the source neutron energy and may require a neutron threshold energy for interaction. In the above plots (background subtracted), the 1236 keV iron peak drops in count rate after switching from a DT (14.1 MeV) to a DD (2.45 MeV) to a <sup>252</sup>Cf (1-2 MeV) neutron source. Table 2 shows the raw ratios of counts between the iron and nickel photopeaks for the Odessa and Sericho meteorites. These values are derived from Table 3, which shows the count rates measured from our datasets for Fe, Ni, Si, S, Mg, Mn, and Co using DT, DD, and <sup>252</sup>Cf neutron sources.

unt rates (A) for Fe and Ni we can derive the approximate wt% in	Sample	Source	Peak Ratios (counts per second/counts per second) based on peak energy (keV)			
r sample for Ni. $A_{Ni}$ . $\sigma_{Fa}$ . $arepsilon_{Fa}$	Sample		Fe/Ni (847 keV/1454 keV)	Fe/Ni (1408/1454)	Fe/Ni (1236/1454)	
$Abundance (wt\%) = \frac{A_{Ni}}{A_{Fe}} \cdot \frac{\sigma_{Fe}}{\sigma_{Ni}} \cdot \frac{\varepsilon_{Fe}}{\varepsilon_{Ni}}$	Odessa	DT	49.4484	1.5757	1.3490	
$A_{Fe}$ $O_{Ni}$ $\varepsilon_{Ni}$	Odessa	DD	43.6763	1.5648	1.1367	
r our samples we found that the Odessa IAB-MG has a Ni	Odessa	<sup>252</sup> Cf	53.0919	1.4230	4.0106	
undance of ≈ 6.1 - 6.3 wt%, which is similar to the published value	Sericho	DT	78.8925	2.6615	18.0120	
7.35 wt% [12]. The Sericho pallasite has a Ni composition of ≈ 3.38	Sericho	DD	29.1944	1.6012	1.1175	
1. 15 wt% which is near the expected value of 4-5% [13-15]	Sericho	<sup>252</sup> Cf	31.7077	0.9833	2.4614	

Sample	Source	847 keV	1779 keV	2232 keV	1454 keV	1408 keV	1332 keV	1236 keV	1434 keV	1810 keV	1369 keV
Sample	Jource	CPS									
Odessa	DT	144.8289	N/A	0.9739	2.9289	4.6150	3.3372	3.9511	2.1050	N/A	N/A
Odessa	DD	107.7106	N/A	N/A	2.4661	3.8589	1.7678	2.8033	N/A	N/A	N/A
Odessa	<sup>252</sup> Cf	35.2054	N/A	0.0134	0.6631	0.9436	0.5999	2.6594	N/A	N/A	N/A
Sericho	DT	52.8908	11.1617	0.3561	0.6704	1.7843	1.9076	12.0756	N/A	N/A	N/A
Sericho	DD	24.9936	2.5661	0.1303	0.8561	1.3708	0.3750	0.9567	N/A	N/A	N/A
Sericho	<sup>252</sup> Cf	5.6736	0.0018	0.0896	0.1789	0.1760	0.5031	0.4404	N/A	N/A	N/A
Pyrite	DD	16.6678	1.1417	0.1794	N/A	0.1850	N/A	0.4906	0.2306	N/A	N/A
Pyrite	<sup>252</sup> Cf	7.9611	0.0343	0.4973	N/A	0.1585	0.3011	0.5761	1.8988	N/A	N/A
Basalt	DD	0.9383	1.7633	0.1172	N/A	N/A	N/A	N/A	0.2208	N/A	0.4497
Basalt	<sup>252</sup> Cf	6.0645	1.3358	0.1434	N/A	0.0545	0.3048	0.3216	1.9146	0.7181	0.8497
Flement Inte	rnreted.	Fe	Si	ς	Ni	Fe	Ni	Fe	Mn	Mø	Mø

## References

[1] Peplowski et al 2012; [2] Prettyman et al 2006; [3] Prettyman et al 2017; [4] Yamashita et al 2013; [5] Peplowski 2016; [6] Evans et al 2007; [7] Elkins-Tanton et al 2016; [8] Lawrence et al 2017; [9] Wasson et al 1960-2001; [10] Peplowski et al 2018; [11] Evans et al 2012; [12] Buchwald et al 1975; [13] Garvie et al 2017; [14] Boesenberg et al 2010; [15] Boesenberg et al 2018; [16] Vidal-Solano et al 2008;

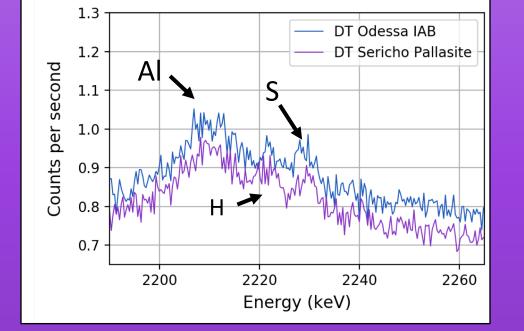
## Sulfur

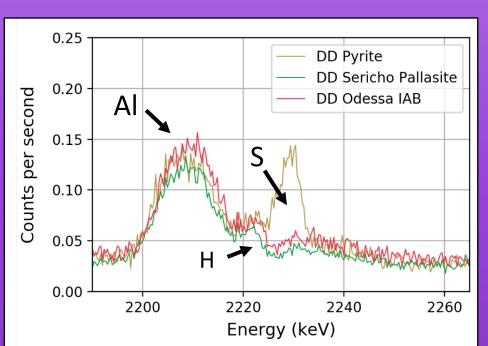
1500

Energy (keV)

The HPGe gamma-ray spectrometer on the Psyche mission has a detection limit requirement of 3 wt% for light elements, such as sulfur. Table 1 shows the approximate wt% S of the Odessa IAB-MG meteorite (0.5 wt%), the Sericho pallasite (3-6 wt%), and the iron pyrite (~53 wt%). The plots below (background subtracted) show the sulfur peak for DT and DD neutron sources incident on both Odessa and Sericho, as well as the sulfur peak for a DD source incident on iron pyrite. The peaks identified in the spectra are Al(n,n'g) at 2211 keV, H(n,g) at 2223 keV, S(n,n'g) at 2232 keV [11]. The sulfur peak appears more prominently in the DT spectra. Table 4 shows the raw ratios of counts between the sulfur and iron photopeaks, as well as the iron and silicon photopeaks for iron pyrite and the Odessa and Sericho meteorites.

2000



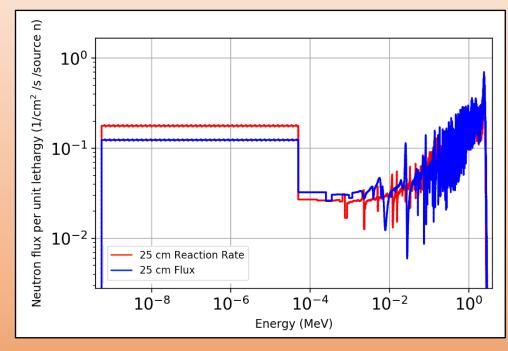


2500

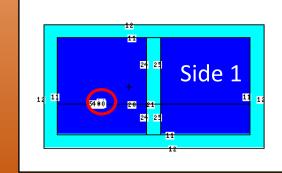
Table 4: S/Fe and Fe/Si Ratios for Selected Samples										
	Source	Peak Ratios (counts per second/counts per second) based on peak energy (keV)								
Sample		S/Fe (2232/847)	S/Fe (2232/1408)	S/Fe (2232/1236)	Fe/Si (847/1779)	Fe/Si (1408/1779)	Fe/Si (1236/1779)			
Odessa	DT	0.0067	0.2110	0.2465	N/A	N/A	N/A			
Odessa	DD	N/A	N/A	N/A	N/A	N/A	N/A			
Odessa	<sup>252</sup> Cf	0.0004	0.0142	0.0050	N/A	N/A	N/A			
Sericho	DT	0.0067	0.1996	0.0295	4.7386	0.1599	1.0819			
Sericho	DD	0.0052	0.0950	0.1362	9.7399	0.5342	0.3728			
Sericho	252 <b>Cf</b>	0.0158	0.5095	0.2035	3142.3103	97.4513	243.9333			
Pyrite	DD	0.0108	0.9700	0.3658	14.5995	0.1620	0.4297			
Pyrite	<sup>252</sup> Cf	0.0625	3.1380	0.8634	232.1979	4.6227	16.8015			

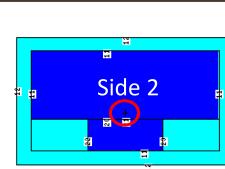
### Simulations

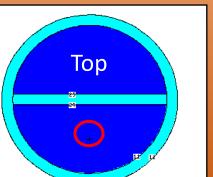
The gamma-ray spectra collected in experiments is directly affected by the neutron environment. In order to better understand the neutron environment we created a model using the particle transport code MCNP 6.1 (Monte Carlo N-Particle). MCNP also allows us to benchmark the instrument response of the detector to actual datasets. The right plot shows a simple neutron flux plot of a DD neutron spectrum tallied on the surface of the iron ball simulated in MCNP.



The figure below shows the geometry of the testing building at LLNL. The room is cylindrically shaped with 3 meter thick concrete walls (cyan), filled with air (dark blue), with an aluminum floor divider. The experiment location is circled in red and is centered on one side of the room.







## Summary & Future Work

- (16) Psyche's unique nuclear environment, along with a high-resolution (HPGe, <3keV at 1332 keV) gamma-ray spectrometer allows us to exploit Fe and Ni signatures unavailable to any previous
- The 1408 keV <sup>54</sup>Fe gamma ray may provide an additional, robust way to determine the Fe/Ni ratio.
- The 2232 keV sulfur gamma-ray was most detectable in samples that used a DT neutron source.
  The Sericho sample needs to be sent out for further
- analysis to determine a more accurate bulk sulfur composition measurement (current estimate is 3-6 wt%) to determine actual detector sensitivity.
- We will continue to explore & characterize signatures that are relevant to Psyche science goals.
- The ultimate project goal is to create a database of relevant lines, similar to Bob Reedy's 1978 paper [17],
- updated for use with metal bodies.
  Repeat measurements with the Psyche Prototype GRS (20% efficiency).

