

Exploring New Signatures for Determining the Ni/Fe Ratio on (16) Psyche. M.T. Burks^{1*}, V.V. Mozin¹, G.B. Kim¹, L.E. Heffern², D.J. Lawrence³, P.N. Peplowski³, J.O. Goldsten³, Z.W. Yokley³, and the Psyche Science Team. ¹Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore CA 94550; ²Arizona State University, Tempe AZ, 85287, USA; ³Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723 USA; *Burks5@llnl.gov.

Introduction: This work explores gamma-ray signatures for determining the Ni to Fe ratio in a metallic body such as the asteroid (16) Psyche. Psyche will be visited by a NASA Discovery-class mission, scheduled to launch in August 2022 [1]. Although gamma-ray spectroscopy has been successfully used on many planetary bodies including the Moon, Mercury, Mars, and several rocky asteroids [2-5], Psyche offers a unique opportunity. This is due to Psyche's unusual composition, expected to be dominated by iron and nickel [1], which will lead to gamma-ray and neutron signatures different from any body previously explored. The Psyche spacecraft will carry a gamma-ray spectrometer that will be able to exploit these new signatures due to its high resolution (~0.2% fwhm at 1332 keV). We are exploring these signatures in the laboratory using Prompt-Gamma Neutron Activation Analysis on iron meteorites of composition similar to that expected at Psyche [6]. The resulting gamma-rays can be used to quantify the elemental and isotopic composition of these samples. First results have demonstrated the value of these alternative signatures. Specifically, it was found that the 1408 keV gamma ray (from ⁵⁴Fe) offers a robust signature for determining the Ni to Fe ratio that is less sensitive to neutron spectral shape and silicate overburden, compared to the 847 keV line (from ⁵⁶Fe) that is typically measured.

Experimental Setup: The experimental setup consists of neutron sources of various energies as well as meteorite samples representing a range of material expected to be found at Psyche. A commercial high-purity germanium detector is used at present, with a high-fidelity Psyche prototype detector to be used in the future. Three different neutron sources are employed: a deuterium-deuterium neutron generator producing monoenergetic 2.5 MeV neutrons; a deuterium-tritium neutron generator producing monoenergetic 14.1 MeV neutrons; and a ²⁵²Cf fission source producing a spectrum of neutrons peaking around 1 MeV but extending as far as several MeV.

The various meteorite samples being measured include an iron IAB-MG (Odessa) and a pallasite (Sericho). Reference samples of relatively pure iron, nickel, cobalt, and aluminum are used, as well as a basalt sample for comparison.

Iron and nickel signatures: The GRS has the primary goal of measuring Ni, Fe, Si, K, S, Al, Ca, Th,

and U, as well as the spatial distribution of Psyche's metal-to-silicate fraction. Each of the elements is detected by a unique set of gamma-ray lines (signatures). The ratio of Ni to Fe is especially important as the Ni concentration, owing to fractional crystallization, is an indicator Psyche's solidification and formation processes.

The baseline gamma-ray signatures for Ni (1454.3 keV for ⁵⁸Ni) and Fe (846.8 keV for ⁵⁶Fe) were chosen because they correspond to the highest cross sections for the highest abundance isotopes of Ni and Fe respectively. Thus, they produce gamma-ray signatures with the highest signal-to-noise ratio.

While no previous planetary mission has measured a significant abundance of nickel, several missions have measured and/or mapped iron [2-5]. These missions used the 846.8 keV line or the 7631 and 7646 keV (thermal capture on ⁵⁶Fe) lines. However, iron produces many more gamma-ray lines of potential interest that were unmeasurable by previous missions due to either the low abundance of iron or the poor resolution of the spectrometer. The Psyche mission, on the other hand, employs a high-resolution gamma-ray spectrometer that is optimized for detection of these key iron lines.

Results: Table 1 lists the gamma-ray lines from iron that have been detected with our laboratory measurements. These are dominated by inelastic scattering of fast neutrons on ⁵⁶Fe. However, the 1408.2 keV line is from inelastic scatter on ⁵⁴Fe. As explained below, this line has many properties that make it very useful as an alternative or complementary signature for determining the Ni to Fe ratio.

Table 1. List of measured iron lines. Lines with significant background (other than Compton continuum) have been labeled with their source. "Ge sawtooth" refers to background caused by the recoil of Ge atoms from fast neutrons.

Energy (keV)	Isotope	Major background source
846.8	⁵⁶ Fe	²⁷ Al, ²⁷ Mg, Ge sawtooth
931.3	⁵⁶ Fe	
1037.9	⁵⁶ Fe	Ge sawtooth
1238.3	⁵⁶ Fe	Ge sawtooth
1303.2	⁵⁶ Fe	
1315.0	⁵⁶ Fe	Very low signal-to-noise
1408.2	⁵⁴Fe	
1671.1	⁵⁶ Fe	
1810.5	⁵⁶ Fe	²⁶ Mg

Figure 1 shows the spectrum resulting from bombardment of an Odessa meteorite with 14.1 MeV neutrons. Shown is the key region containing most of the iron and nickel lines. The baseline signature for determining the important Ni to Fe ratio uses the peak areas from the 1454 keV (^{58}Ni) and 847 keV (^{56}Fe) gamma-ray lines. Note however, that there are many more iron lines detected which could potentially add valuable information.

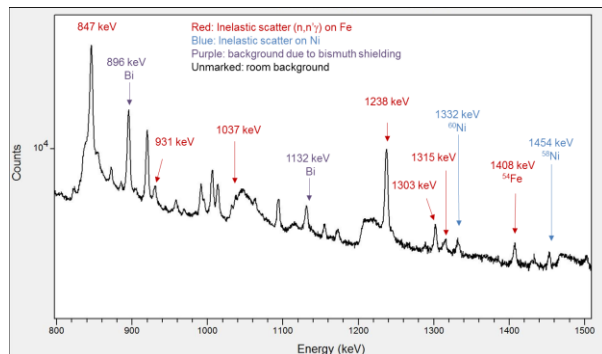


Figure 1. Gamma-ray spectrum using 14.1 MeV deuterium-tritium neutron generator to activate an iron meteorite (Odessa).

Several of the iron lines (1037.9, 1315.0, and 1810.5 keV) suffer from small cross sections for inelastic scatter and/or have strong background interferences, and were ruled out accordingly. Of the remaining lines, it was found that most were very sensitive to neutron energy. Figure 2 demonstrates this effect by comparing the spectrum of the Odessa meteorite bombarded with 14.1 vs. 2.5 MeV neutrons. Note that most of the iron lines disappear when excited by the lower energy neutron source.

On the contrary, the 847 and 1408 keV lines (and the 1454 keV Ni line) all retain nearly constant amplitude in both data sets. This is because these three lines are the nuclear ground-state transitions from inelastic scatter on ^{56}Fe , ^{54}Fe and ^{58}Ni respectively. The other gamma-ray lines are nuclear transitions from higher energy levels, above 2.5 MeV, and are thus not excited by the lower neutron energy. The exception is the 1238 keV line which is the transition from the 2085 keV level to the 847 keV ground state in ^{56}Fe . Thus, while the amplitude is much smaller, it can still be seen in the 2.5 MeV spectrum. This suggests that these lines, and in particular the 1238 keV line, might carry useful information about the neutron spectrum.

Advantages of 1408 keV gamma-ray line to determine the Ni / Fe ratio: Because the 1408 keV gamma-ray line from ^{54}Fe is least sensitive to neutron spectral shape (this was also tested with the ^{252}Cf source, not shown) it can be used, along with the 1454 keV line from ^{58}Ni , to determine the ratio of Ni to Fe with lower systematic uncertainty than other Fe lines. The 847 keV line from ^{56}Fe has the obvious advantage of being much stronger, owing to its higher cross section and higher

isotopic abundance. However, the 1408 keV line has several advantages that should be considered. These include:

Similar efficiency. The 1408 and 1454 keV lines have nearly identical detector efficiency, reducing the need for a correction, even as the efficiency may change over time due to radiation damage and annealing [7].

Insensitivity to neutron spectral shape. Using the 1408 keV should be more robust than the 847 keV line with respect to changes in neutron spectral shape, due to its similarity in energy to 1454 keV. Measurements are in progress to quantify this effect.

Insensitive to silicate overburden. The 1408 and 1454 keV lines will have nearly identical attenuation in the presence of silicate overburden, reducing sensitivity to variations in overburden. This contrasts with the 847 keV line which will require a complex forward model to account for its attenuation relative to 1454 keV.

Similar background. Compared to the 1408 keV region, the 847 keV line sits on a complex background consisting of higher Compton continuum and the presence of a “sawtooth” peak (resulting from the recoil of germanium atoms from fast neutrons).

Fewer interfering lines. 847 keV region includes lines from Al and Mg as well as the radionuclide ^{56}Co (with a 77-day half life, activated by solar flares [5]). These must be accounted for to get an accurate peak estimate. A survey was performed of the 1408 keV region and it was found that there are significantly fewer interferences in that region. Most of these interferences are from high-Z elements that are unlikely to be found at either Psyche or in the spacecraft components, and/or will be very low in abundance.

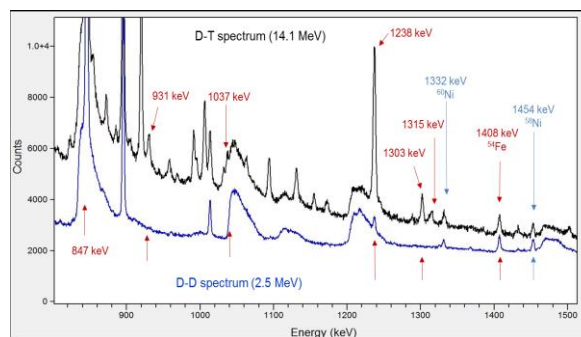


Figure 2. Comparison of two gamma-ray spectra of the same iron meteorite (Odessa) using a 14.1 MeV (top) and a 2.5 MeV (bottom) neutron source. Various gamma-ray lines are highlighted to show how their intensity changes as a function of neutron energy.

References: [1] L. T. Elkins-Tanton et al., 48th LPSC, Abstract #1718, 2017; [2] D.J. Lawrence et al., J. Geophys. Res., 107(E12), 5130, 2002; [3] W. V. Boynton, J. Geophys. Res., 112, (E12), 2007; [4] L. G. Evans, J. Geophys. Res., 117, (E12), 2012; [5] N. Yamashita, Meteoritics & Planetary Science 48, Nr 11, 2237–2251, 2013; [6] L. E. Heffern et al. 100th AGU, Abstract #P53F-3015, 2018; [7] A. Owens, Alan, et al. Journal of Instrumentation 2.01 (2007): P01001, 2007.