ANALYSIS OF COMPLEX GAMMA-RAY SPECTRA: SIMULATIONS FOR PLANETARY GAMMA-RAY SPECTROSCOPY OF SOLAR-SYSTEM BODIES.
J. Brückner[1] , R. C. Reedy[2], P. A. J. Englert[3], and D. M. Drake[4], [1]Max-Planck-Institut f. Chemie (Dept. Geochemistry, Postfach 3060, D-55020 Mainz, Germany, j.brueckner@mpic.de), [2]Planetary Science Inst. (152 Monte Rey Dr., Los Alamos, NM, USA), [3]University of Hawaii at Manoa (HIGP, Honolulu, HI, USA), [4]TechSource (1418 Luisa St., Santa Fe, NM, USA).

Introduction: Planetary gamma-ray spectroscopy (PGRS) is a powerful tool to obtain data on chemical composition of bodies in the solar system. Spacecrafts with a gamma-ray spectrometer (GRS) onboard have orbited the Moon, the asteroid Eros, and Mars, and are planned to orbit Mercury, Vesta, and Ceres.

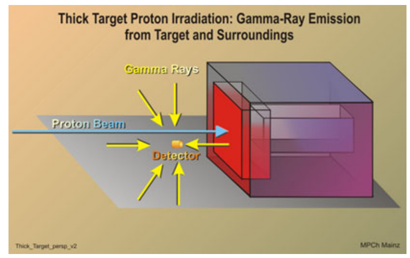
High-resolution gamma-ray (GR) detectors using a germanium crystal reveal the complexity of planetary GR spectra. The production mechanism for most GRs is the interaction of energetic cosmic-ray particles with the upper (10s of cm) surface layer. Secondary neutrons of various energies are produced. These fast, epithermal, and thermal neutrons interact with the nuclei of the surface and produce GRs, mainly by neutron-scattering or capture reactions. Characteristic mono-energetic and background GRs are emitted from the surface and can be measured in the orbit. These data can be converted into elemental concentration maps of the sampled surface provided the methodology is understood in great detail.

To study GR spectra that are comparable to planetary spectra, experiments were performed at the French accelerator SATURNE. The conditions on a planetary surface were simulated by bombarding a thick chunk of matter with energetic protons and simultaneously recording the emitted GRs [1].

Experimental Setup: The planetary surface layer was approximated by a moveable thick target that was sufficiently thick to stop or remove most of the incident proton beam. Five sets of irradiations were done [2].

Thick Target. The thick target consisted of a "surface layer", and an "iron sleeve". The exchangeable surface layer contained material of selected elemental composition, such as basalt bricks. The iron sleeve confines most of the produced secondary particles. One target was almost pure iron. One target was a natural basalt sample. One target had sheets enriched in S and Cl inserted in the surface layer of the basalt, and another target also had hydrogen-rich polyethylene sheets inserted with the sheets enriched with S and Cl.

Proton monitoring. All thick targets were bombarded with 1.5 GeV protons, and the basalt target was also irradiated with 2.5 GeV protons. The beam was pencil shaped, low-flux, and pulsed (spill on and off). The proton spills, which had a fine micro-structure, were monitored by fast scintillation detectors. Their dead time was accurately monitored using a variety of detectors and electronics. The numbers of protons incident on the targets were determined from several beam monitors using dead-time corrections and some corrections for saturation of the beam monitors.



Gamma-ray counting. During the proton irradiations, the GRs emitted by the target and the surroundings were recorded by a high-resolution germanium GR detector. To separate target signals from room background, a 10 cm thick lead shield was periodically placed in front of the target. A hole in the shield permitted the protons to hit the target, but the GRs emitted from the surface were attenuated and did not reach the Ge detector.

The dead times of the detector and all electronics were monitored and corrected. As the rise time of the detector crystal was comparable to the length of the proton micro-pulses, the detector dead time correction could be a potential source of error.

Gamma-Ray Spectra: The final GR spectra of an irradiation experiment were obtained by a multi-step summing process.

Measured GR spectra. The irradiation of each target resulted in four different types of GR spectra, which were recorded when the lead shield was either down or up, each set with either proton spill on or off.

These thick-target spectra are similar to the ones measured by the 2001 Mars Odyssey GRS. Their similarity shows that the experimental simulations reported here were well done. The biggest difference between experiment and the GRS is due to the counts, mainly at higher energies, from cosmic rays passing through the Ge detector. The proton anti-coincidence shield around the Ge detector for the thick-target runs removed such signals successfully.

Evaluation of GR spectra. The GR spectra were evaluated with the fitting program GANYMED. The continuum and the peak(s) were fitted simultaneously. The peak shape consists of two components: a main

Gaussian and an exponential tailing at the low-energy side, each with appropriate parameters. Fitting these parameters, the net peak area is calculated. All peaks exhibit at least some weak tailing, which is caused by incomplete charge collection in the Ge crystal. Increasing radiation damage of the crystal produced by incident protons augmented the amount of tailing, which easily could be handled by the code.

Line identification. Peak identification and association with elements and reactions is based on various databases, such as those used for Mars Odyssey [3]. As the target composition was known in detail, acceptability or plausibility of peak identification could be cross-checked. Some gamma rays were observed from material in or near the Ge detector.

Count rates for peaks. At least two analysts (often more) of the GR spectra determined the fits for peaks using GANYMED or other codes. These results were generally consistent among themselves. The natural widths for most peaks of interest are inside the expected limits. Some peaks are slightly Doppler broadened, such as the $^{28}Si(n,n\gamma)$ gamma ray at 1779 keV. Only a few wide peaks are observed, such as the $^{27}Al(n,n\gamma)$ line at 2211 keV. Only gamma rays that have errors of less than 15 % are included in the final evaluated data sets, except for a few gamma rays if their identification is certain and they are of interest to PGRS. The number of GRs selected is between 163 and 203 for each of the five sets of target irradiations. The number of different gamma rays detected was 272.

Gamma-ray fluxes. The counting rates for prompt gamma rays on the Ge detector from each target were determined using the 4 spectra determined for each set. Counting rates for spill off were used to correct counting rates for spill on for both lead-shield down and up. The gamma-ray fluxes during the lead-shield down irradiations were corrected for background gamma rays using the shield-up measurements using the numbers of protons for both shield down and up and the corrected counting rates. Gamma-ray fluxes were determined for 31 of the strongest gamma rays. These fluxes include many used to determine elemental concentrations in planetary surfaces.

Results. The gamma-ray fluxes for the 5 sets of irradiations were compared to look for trends. Ratios for gamma-ray fluxes were consistent for most evaluated gamma-ray fluxes. Some (e.g., H neutron capture at 223 keV) could not be determined well because of the high room background. However, these ratios often disagreed with ratios calculated using the Monte Carlo N Particle eXtended (MCNPX) code that had been used for Mars Odyssey [4]. The reasons for these differences are not known.

These MCNPX calculations helped to explain the observations, such as the low fluxes of neutron-capture gamma rays from iron being caused by the poor thermalization of neutrons by iron and thus many neutrons escaped from the iron target. The targets with high S and Cl concentration had high cross sections for absorbing thermalized neutrons. The addition of H to the high S and Cl target produced more thermal neutrons, which roughly compensated for the high absorption.

Conclusion: The thick-thick target irradiations provided a controlled irradiation that can be used to better understand the GR fluxes measured by PGRS. The ratios of GR fluxes from targets of known composition can help to interpret spectra obtained by PGRS. So far, these irradiations are the best experimental simulations done for PGRS, as can be shown by the comparisons with a Mars Odyssey GR spectrum.

Many of the results can be used to study backgrounds in planetary or other GR spectra. For example, 26 GRs are observed from neutron-capture reactions with Ge nuclei. About 50 GRs from lead in the shield are observed, as are 10 GRs from the indium seal of the Ge detector's mounting. Many GRs were observed for a number of elements, especially those made by both thermal (e.g. Si, Cl. Ti, and Fe) and fast neutrons (especially Fe). These lists can be useful for workers on future missions to check sources of gamma-rays measured by PGRS.

These results could be used to test calculations for the relative rates for making gamma rays from different elements, as these ratios are fairly-well determined.

References: [1] Brückner J. et al. (1992) *LPS XXIII*, 169-170. [2] Fabian U. et al. (1996) *LPS XXVII*, 347-348. [3] Evans L. G. et al. (2007) *JGR, 112*, E03S04. [4] Kim K. J. et al. (2007) *JGR, 112*, E03S04.

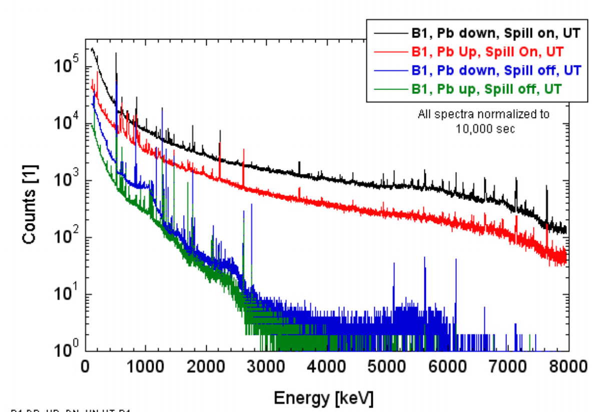


Figure 1 Gamma-ray spectra of basalt irradiated by 1.5 GeV protons, B1, for lead-shield down and up, and proton spill on and spill off, normalized to unit time.