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AUTHOR(S): Robert C. Reedy, Group SST-8

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

# ELEMENTAL MAPPING OF PLANETARY SURFACES USING GAMMA-RAY SPECTROSCOPY*

Robert C. Reedy
Space Science and Technology Division, Mail Stop D438
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

## ABSTRACT

The gamma rays escaping from a planet can be used to map the concentrations of various elements in its surface. In a planet, the high-energy particles in the galactic cosmic rays induce a cascade of particles that includes many neutrons. The $\gamma$ rays are made by the by nuclear excitations induced by these cosmic-ray particles and their secondaries (especially capture or inelastic-scattering reactions induced by neutrons) and decay of the naturally-occurring radioelements. After a short history of planetary $\gamma$-ray spectroscopy and its applications, the $\gamma$-ray spectrometer planned for the Mars Observer mission is presented. The results of laboratory experiments that simulate the cosmic-ray bombardments of planetary surfaces or measure cross sections for the production of $\gamma$ rays and the status of the theoretical calculations for the processes that make and transport neutrons and $\gamma$ rays will be reviewed. The emphasis here is on studies of Mars and on new ideas, concepts, and problems that have arisen over the last decade, such as Doppler broadening and peaks from neutron scattering with germanium nuclei in a high-resolution $\gamma$-ray spectrometer.

## INTRODUCTION

The energies and intensities of $\gamma$ rays escaping from a planet with very little or no atmosphere can be used to map the concentrations of various elements in the top few tens of centimeters of the surface. In the planet, the high-energy ($\sim$0.1–10 GeV/nucleon) particles in the galactic cosmic rays (GCR) induce a cascade of particles that includes many neutrons.[1] The $\gamma$ rays used for chemical mapping are made by the decay of the naturally-occurring radioactive elements (K, U, and Th) and by nuclear excitations induced by cosmic-ray particles (mainly by neutron capture or inelastic-scattering reactions).[2,3] Certain elements, such as hydrogen, carbon, samarium, and gadolinium, can strongly affect the spectrum of neutrons in a planet and thus can be sensed indirectly and their concentration-versus-depth profiles determined from neutron spectra[4,5] or $\gamma$ rays from other elements.[6,7] The Earth's atmosphere is so thick ($\approx$1000 g cm$^{-2}$) that few cosmic-ray particles reach the surface, and it also prevents $\gamma$ rays made in the surface from traveling very far. Thus $\gamma$-ray spectroscopy on the Earth has been limited to low-flying searches for uranium and studies of the cosmic-ray-produced $\gamma$ rays near the top of the atmosphere. Planetary $\gamma$-ray spectroscopy as considered here refer to solid objects with no or thin atmospheres, such as the Moon, Mars, asteroids, and comets.

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The elements that are of interest to future planetary missions are listed in Table I for the Moon, Mars, and a CI-chondritic meteorite. The last composition could be present in asteroids and, with additional amounts of volatile hydrogen, carbon, nitrogen, and oxygen, in a comet. Not listed in Table I are a few minor elements that are enriched in evolved objects relative to most meteorites, such as Sr, Zr, Ba, Gd, Sm, Th, and U. The only $\gamma$-ray-producing reactions of interest with these elements are the neutron-capture ones with Gd and Sm. Also not included is the martian atmosphere, which would add argon to the list, although it is mainly $CO_2$ and some $N_2$. In the Moon, the darker, mare regions are enriched in Fe and Ti, while the lighter colored, highland areas have enhanced amounts of Al and Ca. Considerable variability in elemental concentrations is also expected at Mars.

Planetary $\gamma$-ray spectroscopy was proposed around 1960 by James Arnold and others[8]. However, planetary missions with such instruments have been very rare. On the Apollo 15 and 16 missions in 1971 and 1972, respectively, NaI(Tl) $\gamma$-ray spectrometers were flown, and spectra were accumulated over about 20% of the Moon's surface. Maps of iron, titanium, magnesium, and natural radioactivity were produced from the Apollo $\gamma$-ray data.[9,10] Most existing papers on planetary $\gamma$-ray spectroscopy date back to the Apollo era. Future missions will use advanced technologies for $\gamma$-ray spectroscopy.

A high-purity-germanium $\gamma$-ray spectrometer is scheduled to be launched in 1992 on the Mars Observer, which will be in a polar orbit, and others will probably be on lunar orbiters and Soviet martian orbiters. The Mars Observer Gamma-Ray Spectrometer (GRS) also will include instrumentation that can detect thermal and epithermal neutrons. A $\gamma$-ray spectrometer in a penetrator[11] has been proposed for the comet rendezvous part of the Comet Rendezvous Asteroid Flyby (CRAF) mission. The greatly improved detection capabilities

Table I. Elemental compositions of objects of interest to planetary $\gamma$-ray spectroscopy (mg-element/g-total).

| Element | Average Moon[3] | Mars (Dust)[7] | CI chondrite[12] |
|---|---|---|---|
| H | 0.04 | ~1. | 20.2 |
| C | – | 10. | 34.5 |
| N | – | 1. | 3.2 |
| O | 435. | 442. | 464. |
| Na | 3.5 | 9. | 5.0 |
| Mg | 40. | 40. | 98.9 |
| Al | 110. | 42. | 8.7 |
| Si | 200. | 226. | 106.4 |
| P | 0.6 | – | 1.2 |
| S | 0.7 | 31. | 62.5 |
| Cl | 0.02 | 9.1 | 0.7 |
| K | 1.2 | 1.2 | 0.56 |
| Ca | 100. | 44. | 9.3 |
| Ti | 14. | 4.1 | 0.4 |
| Cr | 1.0 | 1.4 | 2.7 |
| Mn | 0.8 | 3.7 | 2.0 |
| Fe | 90. | 135. | 190.4 |
| Co | – | – | 0.5 |
| Ni | 0.4 | – | 11.0 |

(such as the high resolution for $\gamma$ rays) and new targets (e.g., Mars with its thin atmosphere) have been changing our ideas for planetary spectroscopy considerably since the Apollo days. The Mars Observer GRS is described below. Also discussed are the results of some simulation experiments and preliminary results for $\gamma$-ray and neutron calculations for Mars. The need for data on reactions producing $\gamma$ rays are reviewed. The new instruments will produce significantly improved measurements, but they also require additional studies and calculations to anticipate possible complications arising from their use.

## THE MARS OBSERVER GAMMA-RAY SPECTROMETER

The Mars Observer mission is scheduled to be launched to Mars in September 1992 and will be placed in a polar orbit to globally map Mars.[13] The mission's objectives include determining the elemental composition of surface features and studies of volatile materials (especially water and carbon dioxide), which can be addressed by a GRS on the Mars Observer spacecraft. The martian atmosphere can also be studied by the $\gamma$ rays measured from orbit.[14] From a knowledge of the present state of Mars obtained by the experiments on Mars Observer, the origin and evolution of Mars can be inferred and Mars can be compared with its sister planets the Earth and Venus.[13] A similar spacecraft, the Lunar Observer, has been proposed to do similar mapping of the Moon, but such a lunar mapping spacecraft is not yet an approved mission.

The Mars Observer $\gamma$-ray detector will be a high-purity n-type germanium (hpGe) coaxial diode with a 56-mm diameter and a 56-mm length. It will be cooled to $\lesssim$100 K by a passive radiator. The hpGe will be surrounded by a plastic scintillator, and the GRS's electronics will reject signals in the hpGe detector that are in coincidence with a signal in the plastic scintillator, eliminating background signals from the passage of charged cosmic rays through the hpGe detector. Signals from the hpGe for energies from $\sim$0.2 to $\sim$10 MeV will be processed in a pulse height analyzer. Below and above $\approx$2.4 MeV, the spectra will have $\approx$0.6 and 1.2 keV per channel, respectively. An entire $\gamma$-ray spectrum ($\approx$10,000 channels) will be transmitted every $\sim$20 seconds.

Thermal ($\lesssim$0.1 eV) and epithermal ($\simeq$1-1000 eV) neutrons will be detected using a boron-loaded plastic scintillator for the anti-coincidence shield. The $^{10}B(n,\alpha)^7Li$ reactions induced by these neutrons in the borated plastic will produce a unique signal in the scintillator's output.[15] Because the spacecraft moves at a velocity slightly faster (3.4 km/s) than that of a thermal neutron, the neutron count rates in each of the four faces of the anti-coincidence shield (which is pyramid shaped and fixed relative to the spacecraft's velocity) can be used as a Doppler filter to determine the fluxes and spectral shapes of thermal and epithermal neutrons.[16]

## SIMULATION EXPERIMENTS

Several experiments have been done recently at accelerators to simulate the processes that produce $\gamma$ rays in a planet's surface, and more are planned by the Mars Observer GRS team. In one series of irradiations, thick targets were bombarded with 6-GeV protons,[17] simulating the cascade of GCR particles in a large solid target. The spectra of $\gamma$ rays measured in front of thick iron targets showed many narrow lines whose fluxes were in good agreement with theoretical calculations.[17]

As neutrons dominate the production of most $\gamma$ rays,[2,3] another series of irradiations was done using neutrons from a 14-MeV neutron generator.[18,19] The concrete in the room around the neutron generator moderated many neutrons and produced neutrons with a continuum of energies from 14 MeV to thermal. The $\gamma$-ray spectrum from the irradiation of an aluminum target[19] is shown in Fig. 1. The relative fluxes of $\gamma$ rays made by Fe(n,$\gamma$) reactions were in good agreement with calculated planetary $\gamma$-ray fluxes that only considered production by thermal neutrons.[3] Because the spectrum of neutrons in the simulation had an epithermal/thermal neutron ratio similar to that in the Moon, this agreement shows that thermal yields are good for calculating fluxes of neutron-capture-produced $\gamma$ rays.[18]

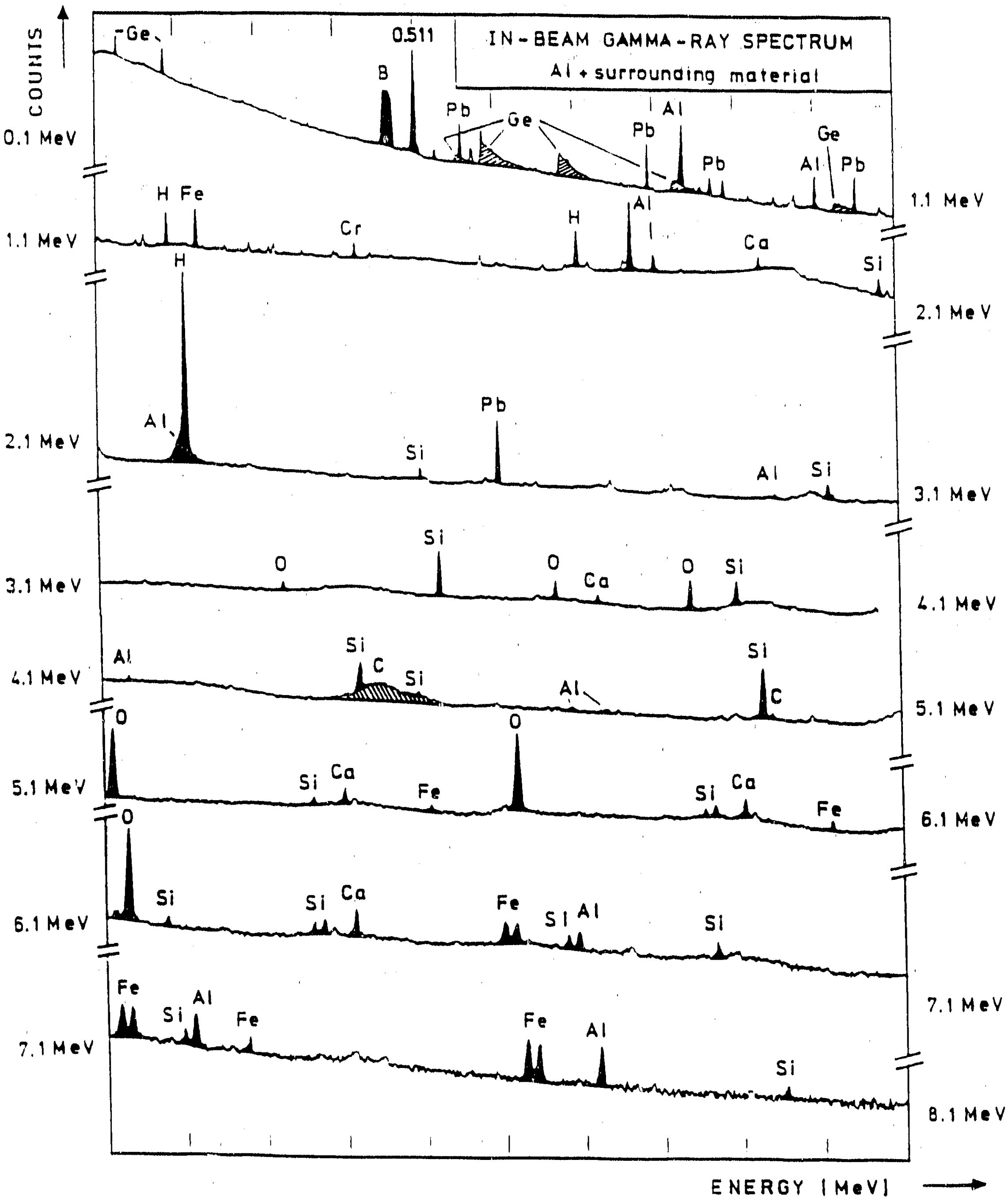
Several aspects of the results for the simulations with $\leq$14-MeV neutrons were different from our experience with the low-resolution Apollo $\gamma$-ray data. As marked with diagonal lines in the top part of Fig. 1, five peaks with unusual shapes were observed. These peaks are shaped normally at their low-energy sides, and their energies correspond to those for the de-excitation of low-lying levels in germanium isotopes. The high-energy sides of these peaks extend for $\sim$50 keV, and are caused by the summing of the recoil energy from a Ge(n,n′) reaction with the de-excitation $\gamma$ ray.[18] Except for the peak at and above 834 keV, these sawtooth-shaped peaks made in a Ge detector should not interfere with the major $\gamma$ rays expected from a planetary surface. The high-energy tail above 834 keV will be under the inelastic-scattering peaks from Al and Fe at 844 and 847 keV, respectively. Also marked in Fig. 1 is the peak at 4.438 MeV from the $^{12}C(n,n\gamma)^{12}C$ reaction (and also probably including some $\gamma$ rays from the $^{16}O(n,n\alpha\gamma)^{12}C$ reaction), which has a width of 53 keV compared to the 5-keV width of an adjacent $\gamma$ ray from Si. This Doppler broadening of the major carbon inelastic-scattering $\gamma$ ray and the low cross section for the $^{12}C(n,\gamma)$ reaction will make the detection of carbon in a planetary surface by high-resolution $\gamma$-ray spectrometers difficult.

## NUCLEAR DATA FOR GAMMA-RAY-PRODUCING REACTIONS

In my 1978 paper on the fluxes of $\gamma$ rays expected from planetary surfaces,[3] I noted that cross sections for the production of $\gamma$ rays by nonelastic-scattering reactions were often scarce. They still are scarce. Usually the highest neutron energy used in measuring cross sections for the production of nonelastic-scattering $\gamma$ rays is below 20 MeV, and often cross sections have not been measured at some energies, such as from $\approx$6-13 or >15 MeV.[20] Few $\gamma$-ray-production cross sections have been measured for the proton energies of interest (hundreds of MeV to several GeV). Recently several irradiations have been done with neutrons having energies $\leq$78 MeV[21] and up to several hundred MeV,[22] and more irradiations are planned to measure such cross sections.

The lack of good cross sections for nonelastic-scattering reactions limits our ability to calculate the leakage fluxes of such $\gamma$ rays, especially for those $\gamma$ rays that are made by high-energy particles and interfere with inelastic-scattering $\gamma$ rays. For example, the production of 1.369-MeV $\gamma$ rays by the $^{28}Si(n,n\alpha\gamma)^{24}Mg$ reaction strongly interferes with the signal from the $^{24}Mg(n,n\gamma)^{24}Mg$ reaction that is used to determine magnesium concentrations.[3] Such interferences by nonelastic-scattering reactions occur for many elements, such as the 4.438-MeV $\gamma$ ray from $^{12}C$ also being produced in high fluxes from

Fig. 1. The $\gamma$-ray spectrum observed from aluminum irradiated with 0 to 14-MeV neutrons.[19] Most $\gamma$ rays were produced in the concrete around the 14-MeV neutron generator and in the material (such as lead and borated paraffin) surrounding the Ge detector. Shaded are the five asymmetric Ge peaks from 596 to 1040 keV and the Doppler-broadened peak at 4.438 MeV from the $^{12}C(n,n\gamma)^{12}C$ reaction (and also probably the $^{16}O(n,n\alpha\gamma)^{12}C$ reaction).[18]



$^{16}O$ or the 1.434-MeV $\gamma$ ray from $^{52}Cr$ being overwhelmed by reactions with $^{56}Fe$.[3] Where such nonelastic-scattering reactions with heavier nuclei interfere with inelastic-scattering $\gamma$ rays, $\gamma$ rays made by neutron-capture reactions often can be used instead,[3] although this is not always the case (e.g., carbon). The $\gamma$ rays made with elements both in the atmosphere and surface, such as oxygen, can often be distinguished by the fact that the width of a $\gamma$-ray line from a solid is almost always narrow while that from a gas usually is Doppler broadened.[14,23] The elements that are generally best mapped by inelastic-scattering $\gamma$ rays include carbon, oxygen, magnesium, silicon, calcium, and iron.

Many elements have sufficiently large cross sections for the capture of thermal neutrons and $\gamma$ rays emitted in large enough yields that they can be studied with such $\gamma$ rays. The fluxes of thermal neutrons in a planet can be considerably modified by light elements, such as hydrogen or carbon, which rapid moderates the neutron spectrum.[5,6] The total cross section for the capture of thermal neutrons also can affect the flux and energy spectrum of low-energy neutrons in a planet's surface.[6] While the fluxes of low-energy neutrons can be calculated well by various codes[4,5,6,7,11,24] for neutron transport, the composition of many martian surface features may not be well determined. Undetected elements, such as gadolinium and samarium, can serious affect the equilibrium neutron distributions.[4,6] Thus elemental ratios will usually be obtained initially from the martian $\gamma$-ray spectra. As iron and silicon have $\gamma$ rays made at good rates by both inelastic-scattering and neutron-capture reactions, their $\gamma$ rays can be used to normalize elemental ratios obtained from both types of reactions.

There is some need for better yields for the production of $\gamma$ rays by the capture of thermal neutrons. The status of the data for the yields of neutron-capture $\gamma$ rays for planetary GRS applications were reviewed over a decade ago[3] and indicated the needed for additional data. Existing compilations[25,26] of the yields of neutron-capture $\gamma$ rays have missed many of the measurements in the literature, and there are not good $\gamma$-ray yields for some of the elements listed in Table I. The elements best mapped by the neutron-capture $\gamma$ rays include hydrogen, aluminum, silicon, calcium, titanium, chromium, iron, and nickel.

## RECENT CALCULATIONS OF MARTIAN NEUTRON AND GAMMA-RAY LEAKAGE FLUXES

In planning for the Mars Observer Gamma-Ray Spectrometer experiment, calculations have recently been done for the production and transport of neutrons[5] and $\gamma$ rays[7] in the martian surface and atmosphere. The attenuation of $\gamma$ rays from the surface by the martian atmosphere[27] needs to be considered in such calculations. All of these calculations included a $\approx$16-$g/cm^2$-thick atmosphere (95.7% $CO_2$, 2.7% $N_2$, and 1.6% $^{40}Ar$) and used a martian-surface composition estimated from chemical analyses by the Viking landers and of the "martian" (SNC) meteorites (the shergottites, nakhlites, and Chassigny).[5,7] Much of the emphasis in these calculations has been on the highly-variable amounts of volatiles ($H_2O$ and $CO_2$) that can be present in or on the martian surface. The equilibrium distributions of neutrons in Mars were calculated using the ONEDANT[5,24] and the ANISN[7] neutron-transport codes. The ONEDANT code was modified to include the effects of gravity and the neutron's beta decay.[24] Neutrons that escape Mars with $E \leq 0.132$ eV are gravitationally bound, although some neutrons beta decay before returning to the planet. Neutron-transport calculations done with and without the effects of gravity showed that gravity increased the flux of neutrons at the top of the martian atmosphere by ≈29%, but that the neutron-flux increase at the top of the soil due to gravity was only a few percent.[24]

These calculations[5,7,24] indicate that the martian atmosphere and the presence of $H_2O$ in or $CO_2$ on the martian surface significantly affect the distributions of neutrons. Hydrogen rapidly thermalizes neutrons and shifts the peak of their depth distribution towards the surface. Because of its low absorption cross section, $CO_2$ builds a large reservoir of low-energy neutrons that can leak back into the surface.[5,24] The neutron count rates expected in the GRS's anti-coincidence shield are high enough to allow a rapid determination of the concentrations of $H_2O$ and $CO_2$ in and on the surface from the observed fluxes and spectral shapes of the thermal and epithermal neutrons.[5] The depth that $H_2O$ is below the surface can often be determined from the neutron[5] and $\gamma$-ray[7] data. Both the measured $\gamma$-ray and neutron leakage fluxes can be used together to get additional information on the concentration and stratigraphy of $H_2O$ and $CO_2$ in the top meter of the martian surface.

The fluxes from the ANISN neutron-transport calculations were used to determine the production rates of $\gamma$ rays by nonelastic-scattering and neutron-capture reactions.[7] The $\gamma$ rays made by these reactions and by the natural decay of K, Th, U, and their daughters were transported through the martian surface and atmosphere to get fluxes at the spacecraft. The $\gamma$ rays most suitable for detecting the expected major elements and the radioelements have strong enough leakage fluxes that they should be detectable with integration times of hours to several hundred hours. The measurement of these elements should aid in the determination of the major rock types present and of the degree of local and global refractory enrichment. Major types of volcanic materials, especially in the southern highlands of Mars unsampled by Viking, should be identified. Readily detectable in $\gamma$-ray spectra will be S and Cl, which might be present in surface precipitates or subsurface brines. Besides elemental abundances, the $\gamma$-ray data can also be used to study the distribution of hydrogen and $CO_2$ in Mars by comparing $\gamma$ rays made by both nonelastic-scattering and neutron-capture reactions with one element.[7]

The data obtained from both the $\gamma$-ray and neutron modes of the Mars Observer GRS will complement each other, and their use together will considerably improve the scientific return. For example, the elemental results from the $\gamma$-ray spectra are needed to help interpret the transport of the leakage neutrons. As neutrons are the major source of most $\gamma$ rays, direct measurement of the neutron leakage flux can aid in interpreting the $\gamma$-ray data. The measured neutron and $\gamma$-ray fluxes also can help to infer the presence of certain elements not directly observed in the $\gamma$-ray spectra, such as relatively high amounts of neutron-absorbing gadolinium and samarium. The intensity of the leakage thermal neutrons can be used with the flux ratio for the neutron-capture $\gamma$ rays from hydrogen and a major element like Si or Fe to determine the concentration and stratigraphy of $H_2O$ in the top $\sim$100 g cm$^{-2}$ of the martian surface or the thickness of $CO_2$ above the martian surface. Such studies of volatiles will be very important not only for studies of Mars but also for comets and possibly for asteroids and the polar regions of the Moon.

## SUMMARY

Future planetary missions to the terrestrial planets and to small bodies (comets and asteroids) will have as one of their major objectives the determination of their chemical compositions. Gamma-ray spectroscopy is an excellent method for orbital or in-situ elemental studies of these objects. Such an instrument is scheduled to fly on the Mars Observer Mission and is a prime candidate for the Lunar Observer mission. Our ideas for these missions have changed considerably since the days of the Apollo missions with their NaI(Tl) $\gamma$-ray spectrometers. New detectors (e.g., high-purity germanium) and techniques (Doppler-filter neutron spectroscopy) are available, and the new targets are different in many ways from the Moon (atmospheres[28] and volatiles). Nuclear data is critical to the planning for and analysis of data from such missions. As discussed above, much work, including simulation experiments and theoretical calculations, is being done in planning for upcoming missions. There is also a strong need for more nuclear data for the production of $\gamma$ rays by inelastic- and nonelastic-scattering reactions and by neutron-capture reactions.

Several problems have been identified with these future $\gamma$-ray spectroscopy experiments. The hpGe detectors can be fairly easily damaged by cosmic radiation. Experiments to understand how and when such radiation damage occurs are being done with the goal of minimizing such effects. The high resolution of hpGe $\gamma$-ray spectrometers increases our ability to measure concentrations of most elements[29,30] but means that we must be careful of effects such as Doppler broadening and interferences to major $\gamma$-ray lines from other sources. The laboratory irradiations and theoretical calculations are important, especially now that we will be going to objects for which we have no "ground truth," which we had at the Moon, to normalize our measurements.[9,31] At present, there appear to be no serious problems to the use of $\gamma$-ray spectroscopy for elemental determinations of a variety of solar-system objects. Additional laboratory measurements, such as $\gamma$-ray production cross sections or yields, will be very valuable for such exploration missions and will help to produce good elemental maps for planetary objects like Mars and the Moon.

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