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AUTHOR(S): ROBERT C. REEDY, Group INC-11, Los Alamos National Laboratory.

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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COSMIC-RAY-PRODUCED GAMMA RAYS IN PLANETARY SURFACES*

ROBERT C. REEDY
Nuclear Chemistry Group, Los Alamos National Laboratory,
Los Alamos, New Mexico 87545, U.S.A.

Abstract A major priority of future NASA planetary missions is the determination of the elemental compositions of solar system objects. Gamma-ray spectroscopy will probably be used soon to determine the surface compositions of Mars and other solar system objects. Neutrons induced by the cosmic rays produce many of the important γ-ray lines that escape from planets. Some measurements of the γ rays produced by neutrons and protons with various energies have recently been made. However, many more nuclear measurements are still needed to plan for and to interpret the results from future planetary missions. Excitation functions for the production of γ-ray lines by both neutrons and protons are needed in calculating the fluxes of γ rays in and above a planet's surface. Thick-target irradiations with high-energy protons have simulated the production of γ rays by the cosmic rays, and more simulations are planned.

INTRODUCTION

As the composition of any object in the solar system is important in determining its origin, evolution, and present state, the determination of elemental abundances has a high priority on future planetary missions. Most future missions will only orbit or rendezvous with planetary objects, such as Mars, the moon, comets, and asteroids. Analyses of the fluxes of γ-ray lines escaping from a planet can be used to map the composition of a planet's surface from orbit if the planet's atmosphere is not too thick.[1] The γ-ray lines made in a planet's surface are mainly from the decay of the natural radioelements (U, Th, and K) and from nuclear reactions induced by cosmic-ray particles.[1] Neutrons made in a planet by the cosmic rays produce most of the γ-ray lines used to determine elemental compositions.[1] Gamma-ray spectroscopy of planetary surfaces has been done before, but much nuclear data are required in planning for improved experiments proposed for future missions.

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GAMMA-RAY PRODUCTION BY COSMIC-RAY PARTICLES

The γ-ray lines used to determine most elements in planetary surfaces are produced by primary and secondary cosmic-ray particles. Each incident particle in the high-energy galactic cosmic rays makes many secondary neutrons.[2] Neutrons with energies from thermal to ~100 MeV produce many of the lines used in planetary γ-ray spectroscopy.[1] Neutron-transport codes have been used to calculate the fluxes of γ rays made by neutron-capture reactions.[1] The chemical composition of a planet's surface, especially abundances of H and of elements with high neutron-capture cross sections, affects the transport of neutrons and the fluxes of γ rays made by neutron-induced reactions.[1,3] Neutron-capture γ-ray lines can be used to map the abundances of certain elements, such as H, Al, Si, Cl, Ti, Fe, and Ni.

Neutron nonelastic-scattering reactions, like $^{16}O(n,\alpha\gamma)^{13}C$ and $^{24}Mg(n,n\gamma)^{24}Mg$, also produce strong fluxes of γ-ray lines. Inelastic-scattering lines can be used to determine O, Mg, Si, Fe, and several other elements in planetary surfaces.[3] Interferences, such as γ rays made by (p,pXγ) reactions, limit the use of certain γ-ray lines in planetary spectroscopy.[3] For example, because iron is much more abundant than chromium, the flux of 1.434-MeV γ rays from $^{52}Cr(n,n\gamma)^{52}Cr$ reactions is usually much less than that from $^{56}Fe(n,n\alpha\gamma)^{52}Cr$ reactions.

Most γ-ray spectrometers proposed for future missions will not use collimation, and the areal resolution on a planet's surface will be about the same as a circle with a radius equal to the spacecraft's altitude,[1,4] which will be ~100 and 360 km for the moon and Mars, respectively. The γ rays that reach an orbiting spacecraft are produced mainly within ~10 cm of the planet's surface. The fluxes of γ-ray lines escaping a planetary surface are low, usually a few photons/cm^2 min or less[3] and the backgrounds are fairly high,[5] so many hours of observing time are required.[4] On the Apollo 15 and 16 lunar missions, NaI(Tl) spectrometers mapped the distribution of Th, K, Fe, Ti, and several other elements over 20% of the moon's surface.[5,6] These lunar measurements confirmed the theoretical calculations.[1,3]

FUTURE PLANETARY GAMMA-RAY SPECTROMETERS

Most future γ-ray spectrometers will use high-purity n-type germanium detectors because of their high resolution[4] and their resistance to radiation damage.[7] On orbiting spacecraft, the detectors usually will be cooled to below 100 K using passive radiative coolers. Such an instrument is being designed for the Mars Observer Mission, which is scheduled for launch in 1990. Similar γ-ray spectrometers also are being planned for flights to the moon and an asteroid that passes near the Earth. Gamma-ray spectrometers could also be used in penetrators on other missions, such as to comets. While we know the basic processes that produce planetary γ rays[1,3] and have some experience from the lunar NaI(Tl) detectors and Ge(Li) spectrometers flown in Earth orbit,[4-6] the use of Ge detectors on planetary missions is new, and much nuclear data are needed to prepare for such missions. High-resolution Ge detectors also introduce a problem not encountered with NaI(Tl) detectors, γ-ray lines that are broadened (such as the 4.438-MeV line from ^{12}C and other nonelastic lines emitted from levels with very short mean-lives).

RECENT EXPERIMENTS RELATED TO PLANETARY GAMMA-RAY SPECTROSCOPY

To help plan for future planetary γ-ray-spectrometer missions, several laboratory experiments have been performed and more are planned. To simulate the cosmic-ray bombardment of planetary surfaces, thick targets have been irradiated with high-energy particles at several accelerators and the emitted γ rays measured. Also, balloons have been used to carry large targets and γ-ray spectrometers to the top of the Earth's atmosphere. Two recent bombardments by A. Metzger and coworkers (priv. comm.) measured the γ-ray spectra from several thick targets with Ge(Li) detectors, and many γ-ray lines were observed. More simulations of thick targets at accelerators or in balloons are planned, including targets with unusual compositions (such as high hydrogen contents).

A few γ-ray spectra have been measured for several targets irradiated by energetic neutrons. J. Brückner[8] used a 14-MeV neutron generator and measured γ-ray spectra from several targets. These spectra showed five asymmetric (tails ~50 keV long on the high-energy side) peaks made at 563, 596, 691, 834, and 1040 keV by inelastic-scattering reactions of neutrons with Ge nuclei. Brückner and P. Englert are using neutrons having energies up to 39 MeV made by d+Be reactions at Jülich, FRG, to measure γ-ray spectra from several targets.

NUCLEAR DATA NEEDS FOR PLANETARY GAMMA-RAY SPECTROSCOPY

Besides the simulation experiments with thick targets that were discussed above, other measurements are needed to plan for and to interpret the results from future planetary γ-ray spectrometers. To interpret the γ-ray spectra obtained from planets, some irradiations of multi-element targets with thermal and epithermal neutrons and with energetic neutrons and protons with a variety of spectra or energies are planned. These γ-ray spectra will allow the relative abundances of elements in a planetary surface to be determined for the two main types of reactions, neutron-capture and nonelastic-scattering. Most elements have strong lines made by one or the other of these two main γ-ray production modes, and several elements (Si and Fe) have relatively intense γ-ray lines made by both types of reactions.

Most of these planetary missions will last for many years. The energetic particles in the cosmic rays, both the GeV ones in the galactic cosmic rays and the ~100 MeV ones occasionally emitted by large solar flares, can induce radiation damage in Ge detectors.[7] Irradiations of Ge detectors by energetic particles are being planned to better understand how radiation damage is produced and to study the rates for producing and annealing such damage.

Excitation functions for the production of γ rays by neutrons and protons are needed to calculate the rates that γ rays are made in a planet's surface.[1,3] The cosmic-ray particles in a planetary surface consist mainly of neutrons below a few hundred MeV and of protons at higher energies.[2] Very few cross sections for the production of γ rays by protons with $E > 100$ MeV have been measured. Many cross sections have been measured using neutrons, but usually only for $E < 20$ MeV, while measurements to ~100 MeV for neutrons and to several GeV for protons are needed. Target elements of interest include O, Mg, Al, Si, Ca, and Fe.[3,4] Some of the existing γ-ray-production cross sections are of poor quality (often measured with NaI(Tl) detectors), as are some of the absolute yields of γ rays from the capture of thermal neutrons.[3]

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