CdZnTe Gamma Ray Spectrometer for Orbital Planetary Missions

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***Abstract*—We present the design and analysis of a new gamma ray spectrometer for planetary science that uses an array of CdZnTe detectors to achieve the detection efficiency needed for orbital measurements. The use of CdZnTe will provide significantly improved pulse height resolution relative to scintillation-based detectors, with commensurate improvement in the accuracy of elemental abundances determined by gamma ray and neutron spectroscopy. The spectrometer can be flown either on the instrument deck of the spacecraft or on a boom. For deck-mounted systems, a BGO anticoincidence shield is included in the design to suppress the response of the CdZnTe detector to gamma rays that originate in the spacecraft. The BGO shield also serves as a backup spectrometer, providing heritage from earlier planetary science missions and reducing the risk associated with the implementation of new technology.**

I. Introduction

Knowledge of surface elemental composition is needed to understand the formation and evolution of planetary bodies. For planetary bodies with thin atmospheres (e.g., the Moon, Mars, Mercury, and protoplanets such as 1 Ceres and 4 Vesta), gamma rays and neutrons produced by the interaction of galactic cosmic rays and solar energetic particles with surface materials can be detected from orbit and analyzed to determine composition. Using gamma ray spectroscopy, major rock-forming elements such as O, Fe, Ti, Al, Si, Mg, and Ca can be detected as well as trace elements such as U, Th, and K with long-lived radioactive isotopes. The addition of neutron spectroscopy enables the mapping of H and rare earth elements (Gd and Sm). Thermal, epithermal, and fast neutron data are also needed to determine the equilibrium density of neutrons in the surface, which is used to convert gamma ray count rates to elemental abundance.

The accuracy of estimates of elemental abundance depends on the pulse height resolution of the gamma ray spectrometer and the ability to suppress or subtract sources of background that interfere with the gamma rays of interest. All successful planetary science missions up to 2001 Mars Odyssey flew low-resolution gamma ray spectrometers based on scintillation technology.[1-4] When scintillation technology is used, few isolated peaks appear in the spectrum and response function fitting techniques must be used to determine count rates for most gamma rays of interest. The accuracy of peak areas determined by these methods depends in large measure on the accuracy of models used to determine the shape of the background. A significant effort continues on the identification and quantification of background sources; however, improved resolution is needed to make significant advances in planetary spectroscopy.

The first mission to fly both gamma ray and neutron spectrometers was Lunar Prospector,[3] which gathered data over the entire surface of the moon. The gamma ray spectrometer (GRS) on Lunar Prospector was a BGO detector, which had a pulse height resolution of 10.5% full width at half maximum (FWHM) at 662 keV at –30°C. The GRS was deployed on a boom to minimize the detection of background gamma rays produced in the spacecraft. High-spatial-resolution maps of the abundance of Th have been constructed using GRS data.[5] Maps of Fe and Ti abundances have been constructed by analyzing the high-energy portion of the pulse height spectrum (above 5 MeV).[6,7] For Lunar Prospector, response function fitting was required to determine peak areas for gamma rays from elements other than Fe, Th, and O.

New planetary science missions are being planned to explore Mercury, Mars, the asteroid belt, and the outer planets. Like Lunar Prospector, most of these missions will use both neutron and gamma ray spectrometers to map elemental abundance. However, due to mission constraints

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(especially mass and heat loading), some of these missions will require instrumentation to be mounted on the deck of the spacecraft, rather than on a boom. For example, missions planned for Mercury, including Bepi Columbo (ESA) and Messenger (NASA), will fly deck-mounted spectrometers.

Deck-mounted neutron and gamma ray spectrometers are sensitive to radiation produced by cosmic ray interactions with the spacecraft as well as radiation emitted from the planetary body. The spacecraft processes gamma rays emitted from the surface of the planet, resulting in increased background continuum relative to boom-mounted systems. The flux of radiation from the spacecraft depends on the mass and composition of the spacecraft and, depending on the altitude of the spacecraft, can exceed the flux of gamma rays from the planet. This source of background radiation can include discrete gamma rays that interfere with gamma rays emitted from the planetary surface. Variations in the mass of neutron moderating material in the spacecraft (e.g. hydrazine fuel), can cause the gamma ray background to vary with time. Consequently, active background suppression systems must be included in deck-mounted spectrometers.

The purpose of this paper is to present the design and analysis of a gamma ray spectrometer based on CdZnTe, a new room temperature semiconductor technology for radiation detection. An array of CdZnTe detectors with signal combination electronics is used to achieve the detection efficiency required for planetary spectroscopy. The use of CdZnTe will provide significantly improved pulse height resolution relative to scintillation-based detectors, with commensurate improvement in the accuracy of estimates of elemental abundance. The spectrometer can be flown either on the instrument deck or on a boom. For deck-mounted systems, a BGO active shield is included in the design to suppress the response of the CdZnTe detector to gamma rays that originate in the spacecraft. The BGO shield also serves as a backup spectrometer, providing heritage from earlier planetary science missions and reducing the risk associated with the implementation of new technology.

II. DESIGN

CdZnTe, a wide band-gap semiconductor, can be used to make gamma ray spectrometers for planetary science. Coplanar grid CdZnTe detectors have the best peak shape and pulse height resolution (usually better than 3% FWHM at 662 keV) and can resolve gamma rays in the energy range of interest to planetary spectroscopy (<9 MeV). However, the size of coplanar grid detectors that can presently be manufactured is less than 2 cm^3 (Fig. 1).[8] In order to achieve sufficient precision for measurements made in orbit, much larger detectors are needed. Consequently, methods to combine signals from multiple detectors to make a large-volume spectrometer have been developed and demonstrated.[9-11] Our goal is to design a CdZnTe array with sufficient resolution and efficiency to detect and resolve gamma rays below 3 MeV. This energy range contains gamma rays for most major elements and all radioactive isotopes.

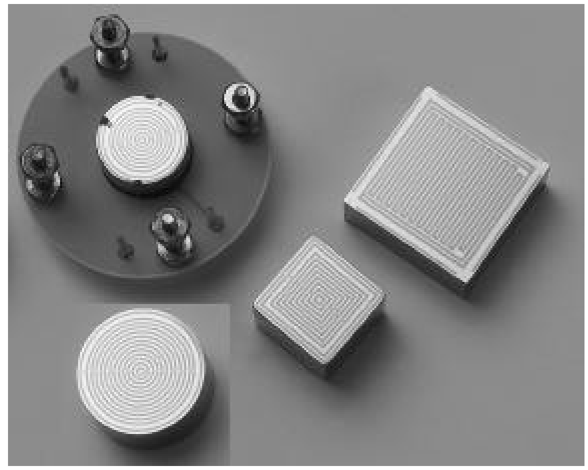

Fig. 1. Coplanar grid patterns developed by LANL and eV Products. The largest crystal shown is 15 mm on a side and 7.5 mm thick.

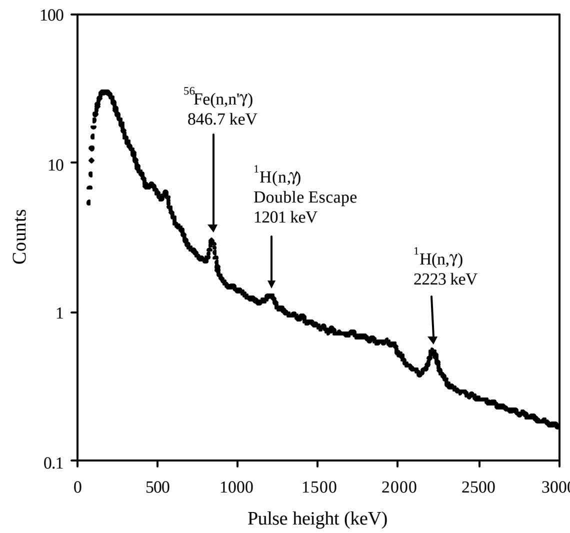

Fig. 2. Gamma ray spectrum measured by an 8-element CdZnTe detector array. The detector array was placed next to ^{252}Cf source, which was surrounded by a large mass of stainless steel.

To demonstrate the performance of a CdZnTe array for the measurement of reaction gamma rays with energies less than 3 MeV, we placed an 8-element array containing 0.5 cm^3 coplanar grid detectors next to a fast neutron source (^{252}Cf), which was surrounded by a large mass of stainless steel. The array and pulse shaping electronics are described in detail elsewhere.[10] The combined pulse height spectrum, shown in Fig. 2, contains the Fe 846.7 keV full energy peak from the ^{56}Fe(n,n′γ) reaction and the full energy peak and double escape peak from the ^{1}H(n,γ) reaction (from H in the surroundings). The resolution of the array was measured to be ~3% FWHM at 662 keV, which is the same as the average resolution of the individual elements.

The energy resolution of coplanar grid CdZnTe detectors varies linearly with energy because the main source of variation from full energy is the uniformity of the charge measurement efficiency within the volume of the detector. Based on experiments, the FWHM of coplanar grid detectors in units of keV can be approximated by $FWHM(E)=aE+n$, where α is a measure of variability in the charge measurement efficiency and n is the electronic noise.[12] For coplanar grid detectors with volumes between 0.5 cm^3 and 1 cm^3, representative resolution parameters are a=0.017/keV and n=6.4 keV. This model gives a resolution of ~2.7% FWHM at 662 keV and ~2% FWHM at 2223 keV, which is roughly a factor of 4 better than that which can be achieved using BGO.

We believe that this level of performance can be achieved routinely by industry. Detectors for a 16-element array with 0.75 cm^3 elements can be manufactured within 1-yr. The cost for procurement of array elements is greater than the cost of components for a scintillation system; however, the manufacturing costs are relatively small part of the total cost of preparing a flight-ready instrument. So, the total cost of a CdZnTe array is expected to be marginally greater than that of scintillation-based systems.

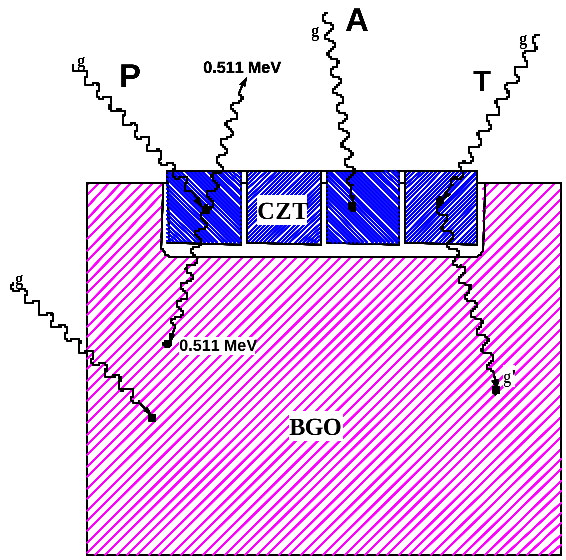

Fig. 3. Arrangement of sensitive elements in a deck-mounted spectrometer for planetary science. The design includes a 16-element CdZnTe (CZT) detector array as the primary spectrometer and a BGO active shield to suppresses the response due to gamma rays originating in the spacecraft. Gamma ray events (labeled A, P, and T) correspond to the different kinds of signatures that can be acquired by the CdZnTe-BGO detector (see text).

A. *Arrangement of Sensitive Elements*

The arrangement of sensitive elements in the gamma ray spectrometer proposed for planetary science applications is shown in Fig. 3. The CdZnTe detector will consist of a 4×4 array of 0.75-cm^3 coplanar grid detectors (for a total active volume of 12 cm^3). Each detector will have a pulse height resolution of ~2.7% FWHM at 662 keV or better. The array will be shielded from the spacecraft by a BGO detector (the array is outward-facing). The thickness of BGO between the CdZnTe detector and the spacecraft is 5 cm. In practice, the CdZnTe and BGO detectors will be surrounded by a boron-loaded plastic anticoincidence shield, which will reject cosmic ray events and acquire fast and epithermal neutron data. The surrounding plastic will also serve to reduce the dose from low-energy charged particles (e.g. solar energetic particles) to the CdZnTe. The mass of the detector, including the plastic shield, photomultiplier tubes, and electronics is expected to be <9 kg.

B. *Signal Processing*

Signals from individual CdZnTe detectors and the BGO detector will be combined on the spacecraft in a field programmable gate array to produce pulse height spectra and list mode data that will be analyzed on the ground. The analog front end electronics for the CdZnTe array follows designs used in earlier work in which the preamplifier output of the coplanar grid difference circuit for each channel is fed into a linear amplifier and linear gate and stretcher.[10,11] The stretched signals are combined to form a gated sum of the pulses from the individual detectors.

The signal processing electronics will acquire three types of spectra that can be used to determine elemental composition, which are illustrated in Fig. 3: an accepted spectrum, which is formed by events with interactions that occur only in the CdZnTe array (labeled A in the figure); a pair spectrum, formed by events in which an interaction is detected in the CdZnTe array coincident with an interaction in the BGO that produces a pulse within a window about 511 keV (labeled P in the figure); and a telescope spectrum, in which the sum of the pulse height in the array and BGO detector is recorded for events in which the pulse height in the BGO is larger than the pulse height for the array (labeled T in the figure). Each of these acquisition modes is designed to suppress the response of the spectrometer to gamma rays generated in the spacecraft. The CdZnTe spectra will be binned on 2048 channels spanning 9 MeV (~4.4 keV/channel). The data telemetry rate is expected to be <3 kbps.

C. *Mechanical Design*

The mechanical design of the CdZnTe array is shown in Fig. 4. The array is composed of 16 mechanically independent detector modules. Each module consists of a CdZnTe crystal mounted in a 12.7 mm square ceramic shell that supports the crystal on five sides. The electrodes are connected by bond-wire to pins, which pass through the base of the shell. Once assembled, the modules can be handled in the same way as standard circuit components. To assemble an array, the modules are bonded to a printed circuit board using epoxy and the pins are soldered to the front-end of the signal processing circuit. To avoid excessive heating of the array and to minimize the space taken by electronic components, only a portion of the preamplifier circuit for each channel (including two FETs) is included on the board. These components provide sufficient amplification to transmit output signals to a separate assembly containing the signal processing electronics.

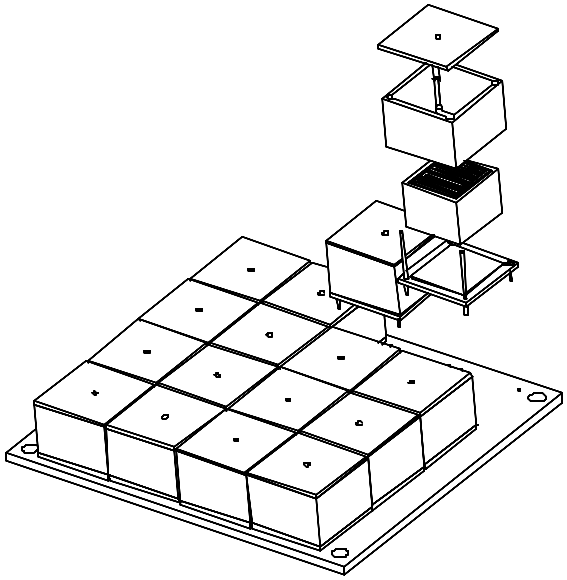

Fig. 4. Mechanical design of a 16-element CdZnTe (CZT) array for planetary science missions.

The array is designed to withstand the dynamic and thermal environments it will experience from launch through end-of-mission. Although a full 16-element array will not be constructed until the CdZnTe concept is selected for a mission, we are currently building a 4-element prototype array that will be flight qualified at the subassembly level based on the IEEE-STD-1156.4-1997.

D. Radiation Damage

Future planetary missions could last as long as 10 years from launch to end-of-mission. During this time, the detectors and electronic components will be exposed to radiation in the form of solar energetic particles and galactic cosmic rays. The total dose to instrumentation depends on a number of factors, including mission duration, solar activity, shielding, and the radiation environment during cruise and in the vicinity of the planetary body. The dose to CdZnTe modules for a mission to Mars or the asteroid belt is expected to be ~0.2 kilorads/yr (including a radiation design factor of two).[13] This estimate assumes that the effective thickness of the housing (including the boron-loaded plastic anticoincidence shield) is 2.7 g/cm^2. The use of a boron-loaded shield will also prevent significant activation of the CdZnTe by thermal neutrons produced in the spacecraft and planet's surface.

Some radiation damage studies of CdZnTe have been carried out (a review is given by Franks, et al.[14]); however, no published data are available on the performance of coplanar grid detectors following irradiation. These studies conclude that significant changes in performance due to radiation damage can occur for prompt doses ranging between 0.043- and 0.44-kilorads (corresponding to 200 MeV proton fluences ranging from 1×10^{9} cm^{-2} to 1×10^{10} cm^{-2}). The change in performance at these dose levels is thought to be associated with increased electron trapping,[15] which may be partially corrected in coplanar grid detectors by adjusting the gain in the differential bias circuit, which is designed to compensate for electron trapping, or by adjusting bulk bias. It has also been reported that the performance of CdZnTe can be recovered by annealing at room temperature or elevated temperatures.[16,17] This observation casts doubt on the utility of the results of studies on the effect of prompt doses for planning planetary science missions and raises the possibility of implementing engineering controls for extended missions. Further research is needed to fully understand the limitations of CdZnTe technology for space flight.

III. EXPECTED PERFORMANCE

A Monte Carlo gamma ray transport code was used to model the response of the 16-element array to gamma rays produced by galactic cosmic rays in the surface of a planetary body. The uncollided gamma ray fluxes calculated by Reedy, Arnold, and Trombka[18] for the average lunar composition were used in the simulation. The uncollided fluxes were calculated for a semi-infinite slab and are thus valid for measurements very near the surface of the planet. In the Monte Carlo simulation, the uncollided gamma rays were mixed with the continuum background spectrum calculated by Bielefeld[19] for the Apollo spectrometers for the collided component of the response. The continuum background was assumed to contain 90% of the gamma rays incident on the spectrometer. This proportion is based on response function analysis of Lunar Prospector data and is adequate for estimating signal-to-noise ratios for gamma ray full energy peaks.

The Monte Carlo code simulates event mode acquisition by the CdZnTe array and BGO scintillator. Energy deposited in the array is converted to pulse height using a response model that includes lower level discriminator settings and the energy-dependence of the resolution of the BGO detector and CdZnTe array elements. The resolution of each CdZnTe detector was assumed to be 2.7% FWHM at 662 keV and allowed to vary linearly with energy (as described previously).

Gamma rays originating in the spacecraft were modeled using the same spectrum used for those emitted by the planet. The mixing of gamma rays from the surface and the spacecraft was assumed to be 1:1. While this is by no means an accurate model of the energy distribution of gamma rays from the spacecraft, it is useful in providing a measure of how effectively the BGO shield and signatures can suppress the spacecraft background. The accepted spectrum was found to be most effective, providing a factor-of-five suppression above 500 keV. The pair spectrum provided a factor-of-three suppression and the telescope spectrum provided a factor-of-two suppression.

Simulated pulse height spectra for the three acquisition modes are shown in Fig. 5. The telescope spectrum (labeled T in the figure) provides the highest detection efficiency, but the resolution is limited by the BGO. The process of unfolding

BGO planetary spectra above 5 MeV to determine Fe, Ti, Ca, and O demonstrated using Lunar Prospector data can be applied to this spectrum.[6] In the pair spectrum (labeled P in the figure), a double escape peak is resolved, which contains contributions from both Ti and Ca. Note that single escape events are less probable than double escape events because the CdZnTe array is thin. The accepted spectrum (labeled A in the figure) provides improved pulse height resolution relative to the telescope spectrum and improved efficiency relative to the pair spectrum.

The accepted spectrum contains intense, well-resolved peaks for Fe, Al, Si, Mg, K, and Th in the region below 3 MeV (Fig. 6). Minor peaks for Ca and O are also present in this region. In addition, this region contains the 2223 keV gamma ray from the ^{1}H(n,γ) reaction. This information in combination with the analysis of the high-energy region of the telescope spectrum (which uniquely provides Ti along with independent estimates of Fe, Ca, and O) is sufficient to meet data requirements for most planetary science missions. The origin of these gamma rays and their intensities (net and background count rates) are given in Table 1.

IV. ANALYSIS AND DISCUSSION

The performance of the spectrometer for the average lunar composition can be used to make rough estimates of the uncertainty in elemental composition for a variety of mission scenarios. Scaling of low-altitude count rates given in Fig. 5 and Fig. 6 and Table 1 to different mission scenarios can be accomplished using the following equation

$$C = C_0\left[1-\sqrt{1-\left(\frac{R}{R+h}\right)^2}\right], \qquad (1)$$

where C is the expected count rate, C_0 is the count rate at low altitude (given in the table and figures), R is the radius of the planetary body, and h is the altitude of the spacecraft.

The relative uncertainty in the net counts (associated with statistical fluctuations in measured count rates) for any peak listed in Table 1 can be estimated by

$$\frac{s}{N} = \sqrt{N + B\left[1+\frac{6/m}{2.35a}(\alpha E+n)\right]}\Big/\left(N\sqrt{t}\right), \qquad (2)$$

where N and B are the expected net and background count rates given in Table 1, respectively; t is the counting time in days; a is the number of channels per keV ($1/a$=4.4 keV/channel); m is the number of channels used to estimate the background underneath the peak; and α and n are the resolution parameters for the CdZnTe array given earlier in the paper. Note that N and B must first be adjusted for the specific mission parameters (altitude of the spacecraft and

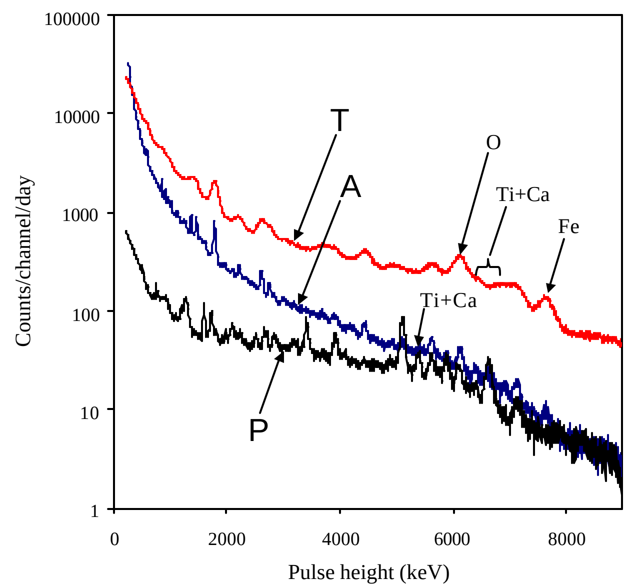

Fig. 5. Simulated pulse height spectra for the CdZnTe-BGO detector for the average lunar composition. Gamma ray events (labeled A, P, and T) correspond to the different kinds of signatures that can be acquired by the detector (see text). Count rates are given in counts per second per day. There are 2048 channels in each spectrum.

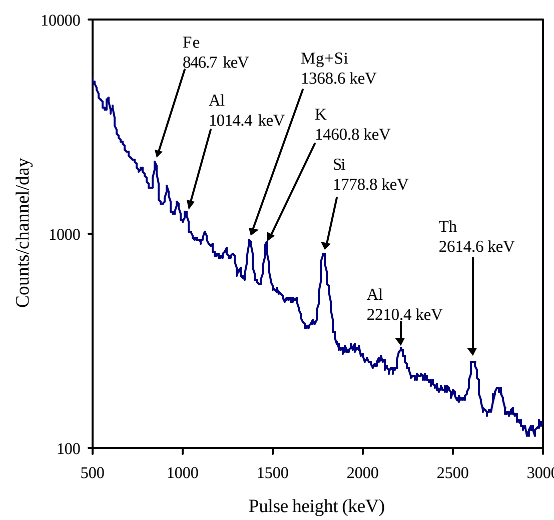

Fig. 6. Simulated accepted spectrum (below 3000 keV) for the average lunar composition. Gamma rays from major elements and radioactive elements are labeled. For reaction gamma rays, the target element is given.

Table 1. Accepted-spectrum peak areas for selected gamma rays below 3000 keV. Reaction types are neutron inelastic reaction (N), proton inelastic reaction (P), and radioactive decay (D).

Residual nucleus	**Element**, reaction type	Energy (keV)	Net peak area (counts/day)	Background (counts/day)
^{56}Fe	**Fe**, N	846.7	2510	26070
^{27}Al	**Al**, N	1014.4	362.9	11020
^{24}Mg	**Mg**, N; **Si**, P	1368.6	2446	13150
^{40}Ca	**K**, D	1460.8	2191	11960
^{28}Si	**Si**, N	1778.8	5107	11810
^{27}Al	**Al**, N	2210.4	671.3	6217
^{208}Pb	**Th**, D	2614.6	979.0	4235

radius of the planetary body) using Eq. 1. The model on which Eq. 2 is based is a standard 3-region-of-interest (ROI) background subtraction model in which channels on either side of the peak are used to estimate the background: $N=G-cD$, where $c \cong m/[6(aE+n)/2.35a]$ is the ratio of the number of channels used to estimate the background to the number of channels in the peak ROI, G is the number of counts in the peak ROI, and $D=c(Bt)$ is the number of counts in the channels used to estimate the background. In deriving Eq. 2, we assumed that G and D were Poisson random variates.

For illustration, consider the determination of the abundance of Fe on Ceres, which has a radius of 471 km, in a circular mapping orbit with an altitude of 125 km. For the 846.7 keV peak, the net count rate is 972 counts/day and the background count rate is 10100 counts/day after correcting the data in Table 1 using Eq. 1. Using Eq. 2, and assuming a single background channel is available on either side of the peak (m=2), the time required to achieve a relative error of 10% in the net counts is ~9 days. For inelastic reactions, large corrections based on neutron count rates are not required. So, the relative error in net counts is approximately equal to the relative error in elemental abundance.

At 125 km, the spatial resolution of the spectrometer on the surface of Ceres is roughly 190 km, which means that the surface of Ceres can be divided up into ~50 area elements. A typical mission to Ceres is expected to spend 6 months in mapping orbit. The relative uncertainty in elemental composition over each of these area elements for a 6 month integration time is predicted to be ~15%, which is adequate for mapping purposes.

V. CONCLUSIONS

The Monte Carlo simulation shows that the CdZnTe detector with a BGO anticoincidence shield will provide ample pulse height resolution and counting efficiency for future planetary missions. By improving pulse height resolution by a factor of four at low energy (relative to BGO), the CdZnTe detector will be able to make accurate measurements of elements that are currently difficult to measure using scintillation technology. The CdZnTe array is based on available technology and can be constructed at relatively low cost and delivered for spacecraft integration in <18 months. The BGO shield provides adequate suppression of gamma rays originating in the spacecraft, enabling the gamma ray spectrometer to be mounted on the deck of a spacecraft. Work is underway to develop a prototype, flight qualified 2×2 array of coplanar grid detectors. Radiation damage studies will be carried out on individual detectors to determine exposure limits and to identify engineering measures that can be taken to extend the lifetime of array elements in the space environment (including anneal cycles and adjustment of bias and gain parameters).

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