CONSIDERATIONS FOR PLANETARY GAMMA-RAY SPECTROSCOPY OF THE SURFACE OF MERCURY; J. Brückner, U. Fabian, M. Wieder, Max-Planck-Institut f. Chemie, Mainz, Germany.

To approach basic scientific questions on the origin of Mercury one needs data on its bulk chemical composition, which can be infered from the elemental composition of the planet's surface. Planetary gamma-ray spectroscopy is a very capable tool to explore the surface of Mercury from an orbiting spacecraft. The gamma rays emitted from the surface carry information on the composition of the surface and the measured gamma-ray data can be used to derive the elemental concentration of many elements present in the surface. A germanium detector would be the best choice for these tasks, provided the problem of cooling can be solved in near future. Otherwise, the usage of suitable scintillation detectors has to be considered. In any case, sufficient information will be obtained to contribute substantially to the exploration of Mercury.

Planetary gamma-ray spectroscopy is considered as a key technique for the exploration of a planet. A gamma-ray spectrometer was on board of the lost Mars Observer spacecraft [1]. NASA is planning on a second mission to Mars and a gamma-ray spectrometer will be on board, again. Currently, the European Space Agency (ESA) is studying a mission to the planet Mercury and among the primary payload a gamma-ray spectrometer is listed.

Little is known about the planet Mercury, since terrestrial observations are very difficult because of the close proximity to the sun and, secondly, so far only one spacecraft, Mariner 10, visited Mercury in three fly-bys. From this visit the high density (5.4 g/cm^3) of Mercury was confirmed, which emphasised the puzzle, that Mercury is too heavy compared to the volume and weight of other terrestrial planets. One plausible assumption is, that Mercury contains a large core (about 70 % metallic phase) and a relatively small mantle (30 % silicate phase). By using the tracking data of an orbiting spacecraft one could measure higher-order terms of the gravitational potential and derive the core size and density distribution. If one could measure the elemental composition of Mercury's surface, a distinction of scenarios of the ancient history of Mercury could be done.

One scenario would be that due to unspecified processes the iron/silicon ratio in the feeding zones of Mercury was changed. However, about a fivefold increase of the Fe/Si ratio is required to account for an iron core of the size needed. One could speculate that in the proximity of the sun the conditions were highly reducing so that other elements like silicon would become metallic and hence contributing to the core phase. As a consequence the Mercury mantle and crust should contain only very little FeO. The elemental composition of the surface should mirror this kind of scenario. An other hypothesis assumes that the accretion of Mercury was similar to other terrestrial planets. Later, Mercury suffered from giant impacts leading to the loss of a substantial portion of the mantle. Also, this would be reflected in the composition of its surface [2].

The average potassium/uranium ratio of the Mercury surface would show if this ratio would decreases with decreasing distance from Sun; e. g. Mars has K/U = 19000 and Earth 11000 [3]. These features can only be revealed by determining the elemental composition of the Mercury surface.

Since Mercury has no atmosphere and only a very weak magnetic field the energetic galactic cosmic rays are permanently bombarding its surface. The resulting interactions of the particles with matter are the main sources of gamma rays. Since the production process of secondary particles is very complex, the major portion of the gamma rays belongs to an continuum, a rather featureless distribution of gamma-ray energies spread over a range from about several 10 MeV down to tens of keV. The production of secondary neutrons provides typical reactions inside the surface that result from $(n,n\gamma)$ scattering reactions and (n,γ) capture reactions of fast and thermal neutrons, respectively. These two neutron-induced reactions are a major source for the production of discrete-energy gamma rays that carry information about the nucleus which emitted them. These gamma rays are diagnostic for the composition of the surface material and can be used as an analytical tool. Their specific very sharp energies are used for the identification of the nuclei, i. e. the elements present in the surface, while their intensities reflect the concentration of the elements, i. e. qualitative and quantitative analysis of the planetary surface is possible. The former can be done successfully by using high-resolution gamma-ray detectors, such as high-purity germanium detectors [4].

The Mercury Orbiter of ESA has as primary objectives four instruments: magnetometer, imaging camera, gamma-ray spectrometer, and plasma ion sensor. The spacecraft that has to withstand the strenuous thermal environment (up to 25 W/m^2) of the Mercury orbit, will be a spin-stabilized design. The orbit that has to fulfill requests from all instruments will be polar elliptical with a periherm of 200 to 300 km and an apherm of 15000 to 20000 km. This orbit ensures good surface coverage at low altitude for remote sensing and at high altitude for magnetospheric/plasma measurements. The nominal mission will last three Mercury years (263 terrestrial days).

The gamma-ray measurements have to take into account the omni-directional response of the spectrometer and a varying field of view. Since the gamma-ray production in the surface is depth dependent, a self-collimation of the gamma rays restricts the effective field of view as a function of the altitude of the spacecraft. A footprint (or pixel) can be defined as an area on the planet, where 80 % of the radiation originates. Depending on the altitude of the spacecraft the finite size of the planet shrinks the size of the footprint. In its polar orbit, the spacecraft flies over the same footprint at the equator only four times during the nominal mission, except for the polar regions. After each orbital period (about 13 hours), the planet will be rotated by 3° at the equator, which provides sufficient overlap of adjacent footprints. The gamma-ray spectrometer will make short measurements (20 to 60 sec) over each footprint. During each orbit the spacecraft will fly below 1200 km altitude for about 1/2 hour, i. e. the solid angle under which the planet appears is more than $\pi/2$. Approaching and leaving the planet will provide some additional time of measurements, but, with a smaller solid angle. During the encounter phase (periherm passage), the data will be stored on board. Afterwards, in the remaining 10 hours (apherm passage), the data will be downlinked to Earth at a low bit rate. On Earth, the individual spectra together with the position of the spacecraft will be stored in a data base to permit summing of the spectra according to selected criteria. In the beginning of the mission, one can sum spectra of large regions, only, to get good statistics; later on, smaller and smaller regions will be spatially resolved. One straight-forward approach would be to add all spectra measured at a given latitude band and subdivide the bands in smaller areas.

Taking into consideration the given elliptical polar orbit and the given orientation of the spacecraft spin axis, an estimation of the expected planetary gamma-ray flux at the spacecraft and the resulting counting time per surface pixel was accomplished. First, the calculated gamma-ray fluxes from the Moon were taken as a preliminary flux estimation, since Mercury is a very dry body [5]. Second, we used data from our 'Simulation Experiments for Planetary Gamma-Ray Spectroscopy [6]' and scaled the measured gamma-ray continuum, accordingly. Combining the lunar gamma-ray fluxes with the experimentally determined continuum we derived the necessary counting time to achieve an analysis for a given error. The estimation of the counting time for one footprint (for a given altitude) can be seen in Table 1.

One has to keep in mind that the gamma rays are produced in the upper meter of the surface, while due to attenuation only gamma rays that originate from depths down to 40 cm have a change to escape the surface without scattering. In this respect, gamma-ray spectroscopy provides the only known tool to sample several centimetres of surface in contrast to x-rays, which provide information of the upper micrometer, only.

To achieve excellent measurements of the Mercury gamma-rays, a high-purity germanium (HPGe) detector is considered to be the best option. The advantage of a HPGe detector system is based on its excellent energy-resolution, which facilitates the evaluation of the measured spectra, tremendously. The disadvantages of a HPGe system are: the Ge crystal has to be cooled down to temperatures below 115 K; the Ge crystal is subject to radiation damage induced by cosmic-ray particles or by strong solar flares. If the Ge crystal can be kept below 90 K, one year of good performance can be achieved, provided no strong solar flares occurred, otherwise, the energy resolution can degrade so much that removal of the damage is necessary. This can be done by heating the crystal up to temperatures of 100°C for several hours to obtain the original energy resolution, again [7]. Cooling in the Mercury orbit can only be done by using an active cooling device, such as a Stirling cooler. Right now, it seems that Stirling coolers are not suitable for such a mission (they are either too heavy or need too much power, besides vibrational problems); but, given five years of further development, a spaceproof light-weight Stirling cooler seems to be achievable. Therefore, the option for a HPGe gamma-ray spectrometer can be kept open. In case a suitable Stirling cooler will not be available, a scintillation detector, such as NaI or CsI, could be used since they need no cooling. Of course, their energy resolution is much worse compared to HPGe detectors and puts severe restrictions on the evaluation of the accumulated spectra.

Elem.	Energy [keV]	Composition [w-%]	10 %Error TIME [h]	20 % Error TIME [h]	30 % Error TIME [h]
Si	1779	20.00	0.61	0.15	0.07
K	1461	0.12	0.78	0.19	0.09
U	609.3	5.0E-05	1.30	0.33	0.14
Th	2614	1.9E-04	1.49	0.37	0.17
O	6129	43.50	4.02	1.01	0.45
Mg	1369	4.00	4.47	1.12	0.50
Fe	7632	0.90	53	13	6
Ti	6760	1.40	86	22	10
Na	440	0.35	208	52	23
Ca	6420	10.00	216	54	24

Table 1: Counting times for one pixel at a spacecraft altitude of 400 km.

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