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A nuclear spectrometer aboard microsatellites for near-earth asteroids exploration

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Abstract

Small and frequent missions to Near Earth Asteroids (NEAs) using 50kg-class microsatellites are a promising approach for both planetary science and space resources. Low cost, short time delivery, and innovation in technology are tangible advantages of the microsatellite missions. It is essential for the progress of planetary science to obtain elemental compositions of planetary bodies as well as their size, mass, density and geometrical shape. Nuclear spectroscopy supported on neutron and gamma-ray spectrometers (NGS) is a powerful and useful tool for directly obtaining the elemental composition of planetary bodies. Spectroscopic analysis of neutron and gamma-ray fluxes emitted from NEAs surfaces is found to provide useful information in characterizing their elemental composition. We have conducted numerical studies of both neutron and gamma-ray fluxes emitted from NEAs surfaces complemented by basic NGS experiments. The investigation of NGS aboard microsatellite towards the future exploration of NEAs is presented and discussed.

1. Introduction

Asteroids are rocky celestial bodies in the 1 m - 10 km size range, thought to be the building blocks of planets and/or their satellites. Some of the main-belt materials are primordial material that has never differentiated before. Other asteroids are pieces of planetary bodies that were broken apart by a collision during the formation stage of planets. These asteroids are thought to be linked with meteorites. Therefore, the exploration of these tiny asteroids is closely associated with the study on how the solar system formed and evolved.

Part of the numerous asteroids that approach or cross the Earth's orbit are called Near-Earth Asteroids (NEAs). They are not only an important scientific study target but also relevant for space exploration and development because they represent a huge storage of natural resources free of Earth's gravity. NEAs can supply materials for a wide range of operations both in space and on Earth, as they are thought to contain large amounts of water, carbon, structural metals such as iron and aluminum, industrial material such as rare-earth metals, and precious metals.

To approach basic questions on the origin and evolution of planetary bodies such as Mercury, Mars, the Moon, comets, and asteroids, observation data on their chemical composition are essential and indispensable. Nuclear spectroscopy is a powerful method to achieve it and has been widely applied to orbital and landing exploration of extraterrestrial planetary bodies: the Moon, Mars, Mercury and asteroids [1-7].

Gamma ray and neutron radiations are produced steadily by galactic cosmic ray (GCR) interaction with the surface and atmospheric materials of planetary bodies in the solar system, and by the nuclear decay of natural radioisotopes within the solid body. Those produced gamma rays and neutrons leak from the planetary surface bringing along important information about the abundance of major and trace elements. Global mapping of elemental composition by an orbiting spacecraft is thus accessible. The main benefit of joint neutron and gamma ray spectroscopy is the ability to reliably identify elements important to planetary geochemistry and to accurately determine their abundance [5,8].

Hence and with the growing interest on NEAs elemental composition characterization for both planetary science and space exploration, [9,10] it was natural to us taking up the task of studying the expected performance of the nuclear and gamma ray spectrometer (NGS) aboard a deep space microsatellite .

2. Deep space microsatellite

Space activities using microsatellites (microsats) are promising for planetary science development and space resources exploration. With the recent progress in miniaturization and increased capabilities on advanced electronic, materials and information technology, microsats show unprecedented potential on performing successful missions. Despite some limitations in lifetime expectancy and resolution accuracy, microsats are very low in cost and short in delivery time what turns out in huge innovation potential in space systems utilization and also on performance assessment of new technologies.

The use of a 50–100 kg class microsat as miniature deep space probe would make it highly attractive for NEAs rendezvous missions paving the way for the next steps on deep-space exploration [11-14]. Such microsats have light weight engines (e.g. a Xe-ion engine) and can approach small bodies moving near the orbit of Earth. Moreover, they offer a very quick turnaround and an inexpensive means of exploring well-focused, small-scale science objectives.

As an education program in a graduate course, a doctoral student can initiate his researching, proposing and building an instrument, for the retrieval of orbital data for analysis and presentation on a thesis, all within a normal period of postgraduate study. Driven by their own vision and efforts and not limited by high threshold budgets, university teams will be able to launch their own satellite into space reaching a new horizon in space research.

At Waseda University, cub-sats (Waseda sat-1,-2, 1nee -3) developed by students have been launched into space. Deep space microsat carrying a nuclear spectrometer will naturally be the next step. We have started microsat designing and partly fabricate and test their elements including the NGS. In this work, we describe in particular the NGS fitting 50 kg-class microsats for future deep space NEAs exploration.

3. Simulation methods

Our numerical calculations were carried out with the simulation tool PHITS (Particle and Heavy Ion Transport code System [15] and some nuclear models and data libraries [16-20] In this section, we briefly describe details of simulation methods.

3.1. GCR Projectiles

The GCR particles of hydrogen and helium in the energy range of 10 MeV/n-100 GeV/n were assumed as the prevailing projectiles. Energy spectra of the GCR particles are given by the following equations (1) and (2) [21, 22]. The fitting parameters and the normalized constant are determined by BESS and PAMELA observation data in 1997, solar minimum phase (φ = 491 [MV]) [23, 24]. These values are shown in Table. 1.

$$J(E,\phi) = C \times \frac{E\left(E+2m_p c^2\right)\left(E+\chi+\phi e\times\frac{Z}{A}\right)^{-\gamma}}{\left(E+\phi e\times\frac{Z}{A}\right)\left(E+2m_p c^2+\phi e\times\frac{Z}{A}\right)} \quad (1)$$

$$\chi = a\exp(-bE) \quad (2)$$

Table1. Parameters used in Eq.(1)

	C	A	b	γ
H	1.24×10^{6}	780	2.50×10^{-4}	2.65
He	2.26×10^{5}	660	1.40×10^{-4}	2.77

3.2 NEA type targets

In our simulations, four types of elemental compositions are assumed as sample compositions. One is that of Earth's core composition with some light elements [25]. The others are three types of meteorites compositions; C-type, S-type, and Martian meteorites [26-28]. These compositions are shown in Table. 2. They are assumed as the parent bodies of M-type, C-type, and S-type asteroids.

3.3 Target geometry setting

The numerical simulations were divided into two steps to shorten calculation time. The GCR particles were injected into a homogeneous target of 20 × 20 × 20 m^3 to obtain energy spectra of gamma-ray emission on a target area of 10 × 10 m^2. The emission spectra was used in the NGS. The methods of numerical simulations are described in detail in the proceeding of ISTS 2017 by Naito et al. [25] and Ishii et al. [26].

Table 2. Elemental targets composition (wt%)

	Core	C-type	S-type	Martian
H	0.60	2.02	0.33	-----
C	-----	3.46	1.03	-----
O	2.05	46.5	38.9	41.4
Mg	-----	9.55	14.1	9.24
Si	2.05	10.7	17.6	21.7
K	-----	-----	0.08	0.08
Ca	-----	0.93	1.21	5.35
Ti	-----	-----	0.08	0.46
Fe	89.6	18.6	20.7	15.0
Ni	5.40	-----	1.12	-----
Others	0.30	8.80	3.20	6.60

3.4 Neutron and Gamma-ray Spectrometer

The NGS consists on a neutron and a gamma-ray spectrometer. Two kinds of gamma-ray spectrometers are assumed: one employs a high purity Ge detector (HPGe) cooled by a small mechanical cooler, and the other is a scintillation detector of 3" thick x 3" ϕ $CeBr_3$. These detectors are surrounded by a thin (5 mm) plastic scintillator as a veto counter to reject GCR events. The HPGe size is 200 cm^3 while $CeBr_3$ has a 350 cm^3 volume. The densities of these detectors are 5.32 g/cm^3 and 5.2 g/cm^3, respectively. And their energy resolutions in fwhm are assumed to be 3.0 keV at 1.332 MeV for HPGe and 26.5 keV at 662 keV for $CeBr_3$.

On the other hand, the neutron detector measures neutron fluxes in three different energy ranges; thermal (< 1 eV), epithermal (1 eV-500 keV), and fast neutron (< 500 keV). The neutron spectrometer consists on 4 mm thick ^{6}Li-enriched lithium glass scintillator (LiG) , Boron loaded plastic scintillator (BLP; 4"ϕ x 3") surrounded with thin Gd foil for thermal neutron shielding and a plastic scintillator (PLS) to reject GCR charged particles.

4. Results and Discussion

4.1. Samples gamma-ray spectra

The emitted gamma-rays energy spectra from NEAs targets with the elemental composition of Table. 2 are shown in Fig. 1. The differences in the elemental compositions are visible and those are the distributions used to test the gamma-ray spectrometers.

Energy spectra from C-type composition obtained by HPGe detector and $CeBr_3$ scintillator are compared in Fig. 2. Many sharp gamma-ray peaks can be seen in the energy spectrum of HPGe. The differences in energy resolution and the detection efficiency of these detectors clearly appear in the energy spectra. Although the gamma-ray lines emitted from various elements are observed by both HPGe and CeBr3, some gamma-ray lines with close energies at 1.779 MeV and 1.809 MeV24) emitted from silicon and magnesium gamma-ray lines through inelastic scattering reaction are difficult to separate the gamma-ray energy spectra by $CeBr_3$

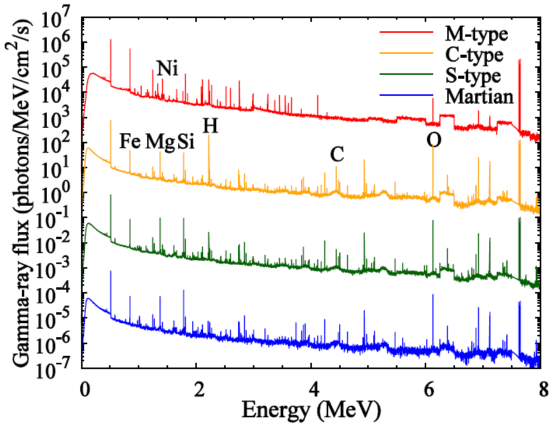

Figure 1. Gamma-ray energy spectra emitted from four different target samples.

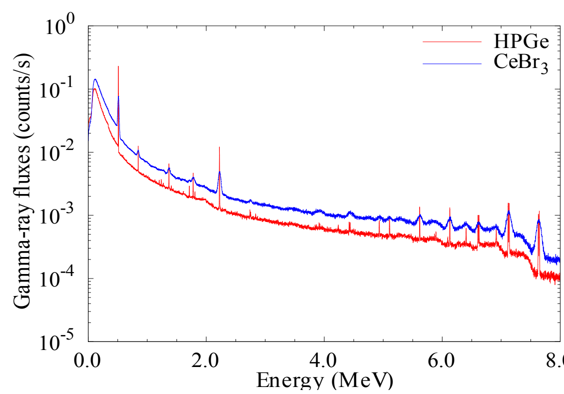

Fig. 2 Gamma-ray energy spectra of C-type composition obtained with HPGe and $CeBr_3$ gamma-ray spectrometers.

4.2 Neutron emission

The target neutron fluxes are shown in Fig. 3. The lowest flux of epithermal neutron is produced by the C-type asteroid as it has the highest hydrogen concentration. There is also a difference in the thermal neutron flux between the S- and M-types. The abundance of Fe and H concentrations greatly affect the energy spectra, especially in the thermal and epithermal energies. Therefore, the measurement of their neutron fluxes provides useful information in determining the NEAs elemental composition.

The estimated neutron counting rates are shown in Fig. 4. The epithermal neutron counting rates detected by the BLP drastically change with the hydrogen concentrations in these meteorites. The counting rates of epithermal neutron detected by the BLP drastically change by concentrations of these meteorites. Therefore, the NS can determine hydrogen concentrations of NEAs surface and will give a constraint on the elemental composition to NEAs by the measurements of neutron fluxes to be obtained by LiG and BLP. As can be seen from Fig.3 and Fig.4, the combination of lithium glass scintillator (LiG) and boron loaded plastic scintillator (BLP) is a good method to measure a wide range of neutron energy and to identify the meteorites and hydrogen-concentration in the meteorites.

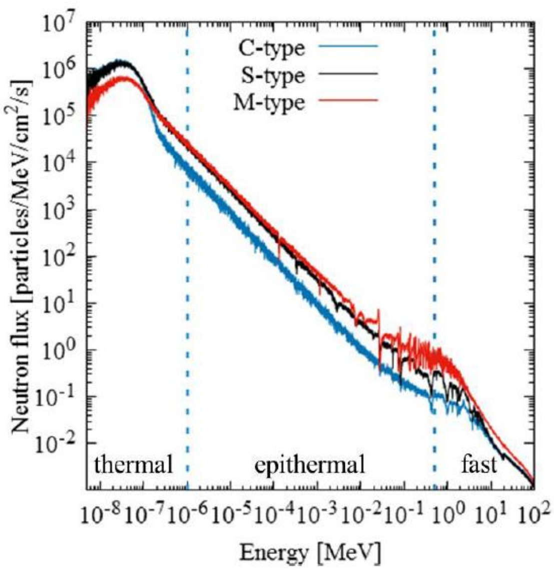

Fig. 3. Energy spectra of neutrons emitted from NEAs with different elemental compositions shown in Table.1.

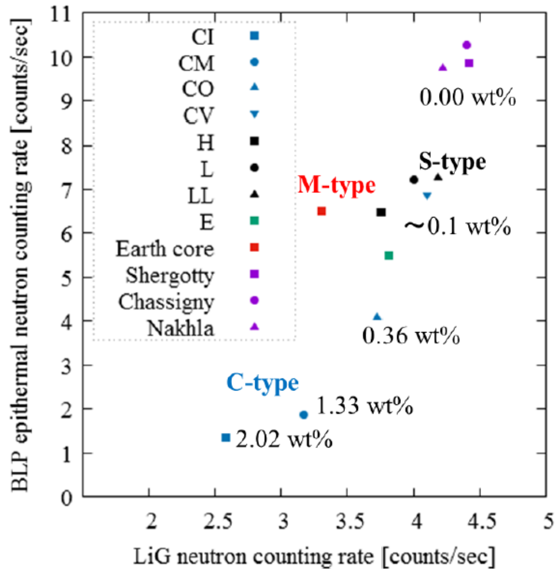

Fig. 4. The correlation of neutron counting rates between LiG and BLP scintillators for different meteorites elemental compositions. The parameter of mass fraction (wt%) in the figure represents the hydrogen concentration in the meteorite composition.

5. Summary and Conclusions

The NGS for NEA exploration based on miniaturized spacecraft, measures the surface abundances of major elements, trace elements, and volatile elements as hydrogen over the whole surface of the NEA bodies. Major objectives for the exploration are to study the NEAs geological features and elemental survey for future space utilization. Gamma-ray and neutron fluxes emitted from different NEA targets types with elemental compositions were numerically calculated for future microsatellite missions. Numerical calculation also tells us that HPGe is better than CeBr3 as gamma-ray spectrometer. However, both the HPGe and CeBr3 are arguably favourable, depending on the mission constraints.

As a general concluding remark we can state that the NGS is proven to be a powerful tool for space science and elemental/geological survey towards the fast approaching miniaturized deep space missions age. In the near future, the NGS carried on a 50 kg-class microsatellite is expected to play an important role in NEAs exploration.

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