Low gamma acrivity measurement of meteorites using HPGe-NaI detector system

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Low γγ activity measurement of meteorites using HPGe–NaI detector system

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Abstract

The radioactivity in natural samples like cosmogenic isotopes in meteorites, in Moon samples, in earth and ice in Antarctica, produced by protons, neutrons, μμ mesons and other charged particles, is very low, usually below 0.001 disintegration per minute per gram. Therefore, very special techniques are required, particularly if the sample cannot be destroyed for chemical separation and system must have possibility of counting large amount of sample. For this purpose we have developed a highly selective Ge–NaI coincidence spectrometer, operating in the underground Laboratory of Monte dei Cappuccini (INAF) in Torino. We have then improved it by developing a multiparametric acquisition system, which allows better selectivity of the coincidence windows (e.g., in meteorites, to disentangle cosmogenic ^{44}Ti signal from overlapping ^{214}Bi, originated by naturally occurring ^{238}U). Applications of this system to the study of meteorites (chondrite, achondrite and iron samples) are described.

Keywords

- γ-Rayγ-Ray spectroscopy;
- Cosmogenic radionuclides;
- Meteorites;
- Cosmic ray flux;
- Coincidence techniques

1. Introduction

Galactic cosmic ray (GCR) particles produce a large number of radioactive and stable isotopes by nuclear interactions in Earth's atmosphere, meteoroids and planetary surfaces. GCR flux varies in the interplanetary space due to modulation effect of solar magnetic field. In particular, the cosmogenic isotopes in meteorites are directly related to GCR flux between about 1 and 3 A.U. before their fall on the Earth, when GCR exposure becomes negligible. Each cosmogenic isotope then preserves the past record of the GCR flux roughly over its mean life and its concentration is not affected by terrestrial climatic and geomagnetic influences, as in the case of ice cores and tree rings.

The measurement of low levels of radioactivity in meteorite samples requires highly sensitive detectors and very special techniques, considering also the fact that specimens cannot usually be destroyed for chemical separation and large amount of sample is required. In order to achieve highest selectivity, we have developed a γγ spectrometer capable of non-destructive measurement of meteorite samples up to ~ 1 kg∼1kg mass and a specific data acquisition system.

2. Experimental procedure and applications

The γ-rayγ-ray spectrometer is a large volume high-efficiency HPGe–NaI(Tl) detector system located in the underground (70 m.w.e., meter water equivalent) Laboratory of Monte dei Cappuccini (INAF, Torino, Italy). This system consists of a hyperpure Ge detector (3 kg, 147% relative efficiency), operating within an umbrella of NaI(Tl) scintillator (90 kg) and is housed in a thick Pb–Cd–Cu passive shield. Both detector signals are digitized by the multiparametric acquisition system allowing coincidence and anti-Compton spectroscopic analyses. The Ge background level in the region of ^{22}Na peak at 1274.54 keV is 4.70±0.15 counts per day/keV, and in the region of ^{26}Al peak at 1808.65 keV it is 1.95±0.09 cpd/keV. The spectrometer is described in detail in Ref. [1] and references therein.

As the meteorite specimens vary in size, shape and composition, the γγ efficiency is specific of each measurement. Full peak efficiency (FPE) values at different γγ lines were first experimentally determined for the Torino *chondrite* (a stony meteorite, fallen in 1988 in Torino; fragment *A*, 445 g) by making an identical mould of the specimen filled with labelled sediment having known amounts of ^{60}Co, ^{40}K, ^{137}Cs, mixed with iron to match the density of the meteorite and assuming uniform distribution of density and radioisotopes.

This technique (a mould which reproduces shape and density) relies on the fact that most of the measured γγ's are in the energy range 300–3000 keV, where the mass attenuation coefficients for different atom species differ at most of a few percent (see Fig. 1, where the values for a few elements relevant in meteorite compositions are shown, data from U.S. National Institute of Standards and Technology [2]).

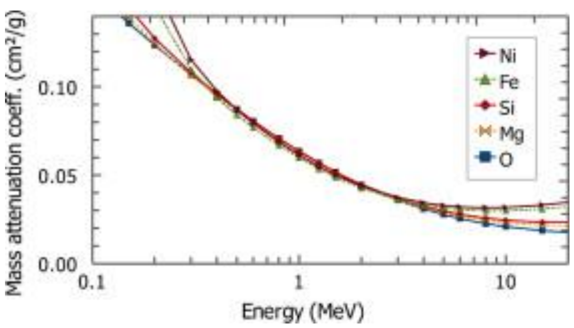

Fig. 1.

Mass attenuation coefficients for O, Mg, Si, Fe and Ni. Below ~0.3 MeV ~0.3MeV energy the coefficient values are affected by atomic shell resonances, whereas beyond ~3MeV higher energy interactions make them depart from each other depending on nuclei mass. Data from NIST [2].

For other *chondrites* , potassium composition (known from chemical analyses) gives ^{40}K γγ emission rate and therefore an acceptable estimate of FPE at 1460.82 keV. Hence FPE in other energy regions was scaled from the ^{40}K efficiency.

Recently we measured also the *non-chondrite* meteorites Almahata Sitta [1] [3] and Gebel Kamil [2] (Taricco et al., in preparation). Fig. 2 shows (a) the two-dimensional spectrum of Gebel Kamil *SE36* meteorite in the region of the 1808.65 keV peak, due to cosmogenic ^{26}Al and (b) the Ge spectrum in *normal* and *coincidence* modes.

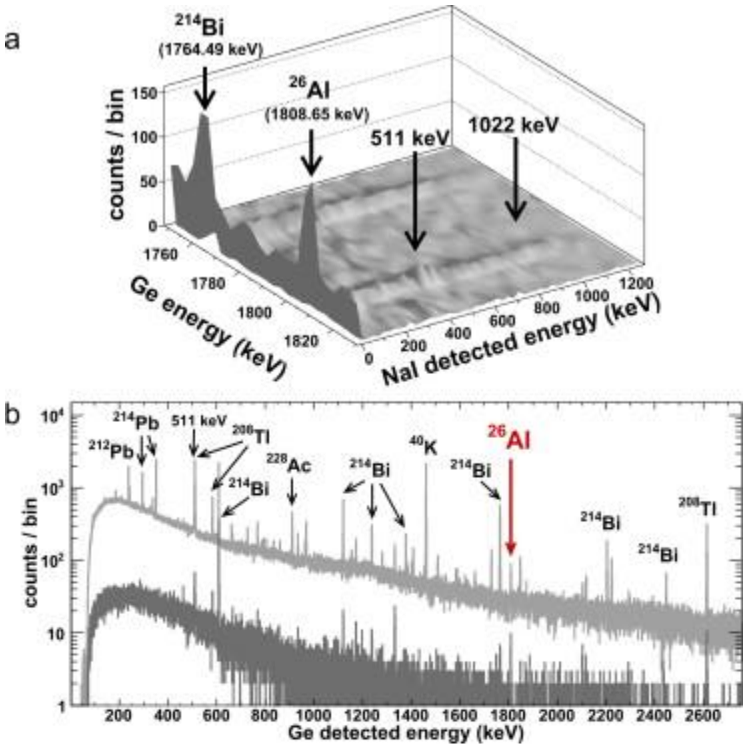

Fig. 2.

(a) HPGe–NaI(Tl) γ-rayγ-ray spectrum of Gebel Kamil *SE36* fragment between 1750 and 1835 keV Ge energies, where cosmogenic ^{26}Al and coincidence with β^+β+ annihilation photons are marked. (b) Ge only spectrum (light grey) and Ge after filtering counts in coincidence with NaI detection of both 511 keV β^+β+ annihilation photons (dark grey). ^{26}Al main peak and a few peaks from the background of naturally occurring potassium, uranium and thorium are marked: ^{214}Pb, ^{214}Bi come from ^{238}U; ^{208}Tl, ^{212}Pb, ^{228}Ac from ^{232}Th.

As ^{40}K γγ emission in Almahata Sitta was below detection level, a mould was prepared to determine the FPE. In this way, the activity of the cosmogenic ^{46}Sc, ^{57}Co, ^{54}Mn, ^{22}Na, ^{60}Co and ^{26}Al was obtained in the specimen and, using ^{60}Co and ^{26}Al isotope depth production profiles, the depth of the fragment inside the asteroid was estimated. Moreover, we pointed out that the high activity of ^{22}Na corresponds to the last prolonged solar minimum [3].

In the case of Gebel Kamil *iron* meteorite, the high density (7.9 g/cm^3) could not be achieved using the iron powder, so self-absorption effects were estimated on the basis of efficiency measurements of a set of different-density moulds. As their geometry is same, an average attenuation length was then estimated and used to calculate the efficiency correction for the density of the meteorite. We detected the cosmogenic ^{26}Al (0.0055±0.0003 cpm; Figs. 2 and 3a), which allowed to estimate that the pre-atmospheric radius of the meteoroid was ~ 1 m~1m and the sample was close to the center. Moreover, the absence of ^{44}Ti signal (at 1157.02 keV; Fig. 3b) suggests a crater minimum age of ~250~250 years.

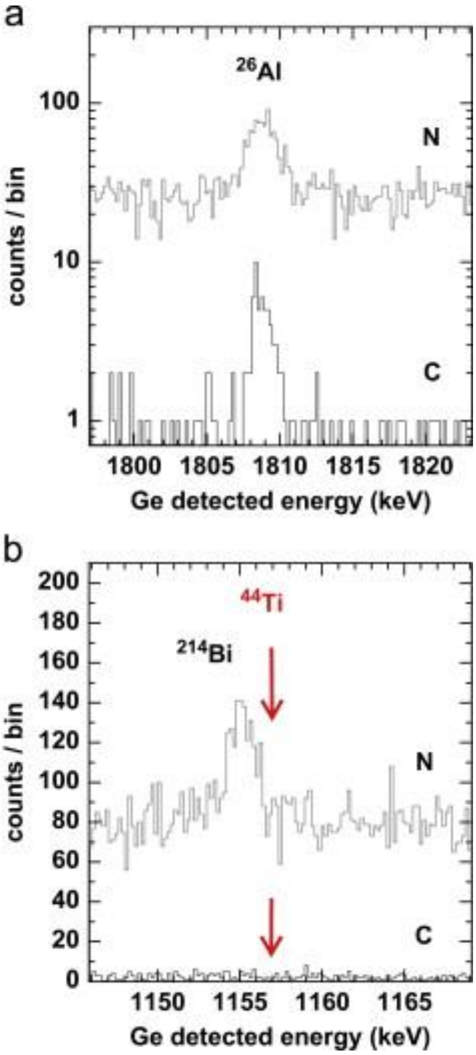

Fig. 3.

Details of Fig. 2b spectrum (Gebel Kamil *SE36* fragment). (a) ^{26}Al main peak at 1808.65 keV in *normal* **N** and *coincidence* **C** modes. (b) Region of ^{44}Ti main peak at 1157.02 keV. The *coincidence* spectrum **C** reduces the background considerably and confirms the absence of ^{44}Ti signal.

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1

A *ureilite* fragment (75 g) ascribed to 2008 TC_3, the first ever asteroid sighted in space before the Earth impact, predicted in North Sudan on next day, October 7, 2008. Although it exploded at 37 km altitude, this and many other fragments were recovered during successive search campaigns in Nubian Desert, in the surroundings of Almahata Sitta (train *Station 6* in local speech) [4].

2

An *iron*, fragment *SE36* (672 g; coordinates 22 00 47.4 N; 26 05 25.5 E), found nearby the Kamil crater, which was previously localized with Google Earth in South Egypt by V. De Michele. Kamil is the first rayed crater found on Earth, therefore it is exceptionally similar to Moon craters and must be relatively recent. Moreover, it is one of the few known small impact craters [5].