Applied Radiation and Isotopes
Available online 10 January 2023, 110651
In Press, Journal Pre-proof

Cosmogenic radionuclides in the Cavezzo meteorite: Gamma-ray measurement and detection efficiency simulations

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https://doi.org/10.1016/j.apradiso.2023.110651

Abstract

The Cavezzo meteorite was recovered on January 4th, 2020, just three days after the fall observed over Northern Italy by the all-sky cameras of the Italian PRISMA fireball network. Two specimens, weighing 3.1 g (F1) and 52.2 g (F2), were collected in the predicted strewn-field and the meteorite has been classified as an L5 anomalous chondrite. The gamma-activity of F2 sample was measured at the Monte dei Cappuccini underground Research Station (Torino, Italy) with a large-volume HPGe-NaI(Tl) spectrometer. Thanks to the high efficiency, selectivity and low background of the spectrometer, we were able to detect fifteen cosmogenic radioisotopes. The presence of nuclides with half-lives down to few days (^{47}Ca, ^{52}Mn and ^{48}V) undoubtedly confirmed the recent fall of the sample. The very low activity of ^{44}Ti and ^{60}Co was revealed with a particular coincidence between the HPGe and NaI(Tl) detectors. To obtain the detection efficiency, we have simulated the response of the detector with the GEANT4 toolkit, once the spectrometer's dead layer thickness was estimated using standards of known activity. Moreover, the simulation of the Dhajala meteorite (H3/4 chondrite) measurement allowed us to verify that the self-absorption of the sample is correctly taken into account and validate our simulations. In this contribution, we focus on the coincidence optimization techniques and the detection efficiency computation.

Introduction

A large number of stable and radioactive isotopes is produced in meteoroids by the interaction of cosmic rays (CR) in the interplanetary space. When a meteoroid enters the Earth's atmosphere and a meteorite sample is collected on the ground, the activity of such radionuclides can be measured. The production of these cosmogenic isotopes ends as soon as the meteorite falls, when the CR flux irradiation ceases. Freshly-fallen meteorites are of great interest in planetary science since they give the opportunity to reveal cosmogenic radioisotopes with short half-lives (days or weeks), that otherwise cannot be revealed in any other natural sample.

The activity of a cosmogenic radioisotope in a meteorite mainly depends on the primary galactic cosmic rays (GCR) flux in space, roughly over few half-lives of the isotope before the meteorite falls on the Earth. It is therefore possible to study GCR flux intensity and its variations over time through the measurement of gamma-activity in meteoritic material. On the other hand, cosmogenic isotopes concentration is an important proxy of the solar activity, which is anticorrelated to GCR flux (Beer et al., 2012).

Freshly-fallen meteorites can be recovered thanks to the observation of their atmospheric transit and the consequent estimation of the strewn-field of survived fragments. This is the operational principle of fireball networks, which usually deploy optical all-sky cameras dedicated to the recovery of such samples. Thanks to the dynamic and photometric analysis of the bright flight, it is also possible to estimate the pre-atmospheric size of the meteoroid and other relevant physical parameters. In this context, the measurement of long-lived cosmogenic radioisotope activity in meteorite samples provides an independent estimation of the meteoroid size. In addition, this measurement allows to define the average shielding conditions of the meteorite during its CR exposure age.

On January 1st, 2020, the PRISMA all-sky camera network recorded a brilliant fireball in the skies of Northern Italy. Thanks to these observations, the expected strewn-field was confined in an area of about 5 km^2 near the municipality of Cavezzo, Modena (Gardiol et al., 2021). Such analysis allowed to recover two meteorite specimens in the predicted area just three days after the event was observed. The analysis of geochemical, mineralogical and petrographic properties of both fragments supported the classification of the Cavezzo meteorite as an L5 anomalous chondrite (Pratesi et al., 2021), being the first of this class. Similar observations about the atmospheric path of fallen meteorites are available only for 35 among all the officially classified meteorites (Colas et al., 2020, Gardiol et al., 2021). The analysis of fresh-fallen meteorites, for which the pre-atmospheric orbit has been determined, is of utmost importance in planetary science, enabling for instance investigations between particular meteorite groups and their source region in the Solar System.

To determine the activities of cosmogenic radionuclides in Cavezzo, we used a large-volume and high-efficiency HPGe-NaI(Tl) spectrometer located in the underground Laboratory of Monte dei Cappuccini (Torino, Italy). Such detectors allow for a non-destructive and highly selective measurement of the gamma-activity of the counted sample. Several meteorites have been measured in this facility (see e.g. Taricco et al., 2006, Taricco et al., 2008, Colombetti et al., 2008, Colombetti et al., 2013, Taricco et al., 2016). In particular, the activity of ^{44}Ti measured in 22 meteorites fallen to Earth in the last 250 years, has been used to probe the GCR flux and solar activity long-term modulation (Asvestari et al., 2017, Mancuso et al., 2018, Mancuso et al., 2019).

The measurement of the main mass of the Cavezzo meteorite indicated the presence of fifteen cosmogenic isotopes with half-life down to few days. In this paper, we focus on the methods developed to identify radioisotopes with low gamma-activity and numerical simulations to estimate the spectrometer detection efficiency. The activity of the cosmogenic radionuclides and the estimated efficiency values will be presented and discussed in a forthcoming publication.

Section 2 gives a brief review of the Cavezzo meteorite recovery, chemical analysis and classification. In Section 3 we describe the instrumental setup, while Section 4 presents the measured spectrum and the counting rates of identified cosmogenic radioisotopes. Section 5 describes the optimization technique for the coincidence between the HPGe and the NaI(Tl) detector signals, used to reveal the faint activity of ^{44}Ti and ^{60}Co. In Section 6 we describe numerical simulation implemented with GEANT4 for the estimation of the dead layer thickness and the detection efficiency of the HPGe spectrometer. We draw our conclusions in Section 7.

Section snippets

Cavezzo meteorite: recovery and classification

The PRISMA network, born in 2016, was conceived to achieve systematic surveillance of the Italian skies to monitor fireballs and bolides (Gardiol et al., 2016, Gardiol, 2019) and is a partner of the Fireball Recovery and InterPlanetary Observation Network (FRIPON) collaboration (Colas et al., 2020). To date, the network deploys almost 70 stations, including operating ones and those in the installation phase, distributed all over the country. Each station is equipped with an all-sky camera...

Experimental setup

The F2 sample was measured at the Monte dei Cappuccini underground Research Station in Torino with a large-volume, high-efficiency HPGe-NaI(Tl) spectrometer, named GEM90 (Taricco et al., 2006). This systems consists of a hyperpure germanium (HPGe) crystal (2 kg, 95% relative efficiency, resolution $\sim$ 2 keV) operating in coincidence with an umbrella of NaI(Tl) scintillator

(55 kg). Fig. 2 shows the F2 specimen located on the top of the Ge crystal, surrounded by the NaI(Tl) annulus. A passive...

Gamma-spectrometry measurement

The measurement of F2 specimen of Cavezzo took place about three weeks after the sample was recovered and lasted ∼ 45 days. The counted gamma-ray spectrum in normal mode (HPGe alone) is shown in Fig. 3. Several peaks are visible, both related to natural (black) and cosmogenic (red) radioisotopes. Thanks to the high selectivity and low background of the system, and to the coincidence between the two detectors, we were able to measure fifteen cosmogenic radionuclides. All the other peaks that...

Coincidence optimization for ^{44} ti and ^{60}co detection

The GEM90 acquisitions on HPGe and NaI(Tl) scintillator are independently recorded by the digital acquisition chain of the detector (Colombetti et al., 2008, Colombetti, 2009), allowing us to obtain independent spectra for the two detectors. Fig. 4 plots the two-dimensional spectrum, that is the number of events recorded in the HPGe detector in coincidence with events on the NaI scintillator, as a function of their energies. For instance, the sharp vertical lines at 1275 and 1809 keV represent...

Detection efficiency simulations with GEANT4

In order to deduce the activity of a radionuclide from the gamma-ray spectrum, it is necessary to estimate the detection efficiency. For this purpose, we used the Monte Carlo simulation toolkit Geant4[4] (Agostinelli et al., 2003, Allison et al., 2006, Allison et al., 2016), useful to simulate the passage of particles through the matter and developed by the Geant collaboration at CERN. It provides an extended library of virtual classes, to be implemented for ...

Conclusions

Cavezzo is an L5 anomalous chondrite felt on January 1st 2020 in Northern Italy and is the first meteorite recovered by the Italian PRISMA all-sky camera network.

Thanks to the high efficiency and selectivity of our gamma-ray spectrometer at the Monte dei Cappuccini underground Research Station, we were able to reveal the presence of cosmogenic radionuclides with half-lives down to few days, thus confirming the recent fall of the sample.

The measurement of the faint activities of ^{44}Ti and ^{60}Co...

CRediT authorship contribution statement

Ilaria Bizzarri: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Dario Barghini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Paolo Colombetti:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Daniele Gardiol:** Writing – review & editing, Supervision, Software,...

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

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