COSMOGENIC NUCLIDE DECAY PEAKS MADE IN GERMANIUM GAMMA-RAY DETECTORS.

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Introduction: Cosmic-ray particles produce many backgrounds in gamma-ray detectors in space, some of which interfere with gamma rays of interest from the studied object. Most background peaks in gamma-ray spectra come from the matter around the detector, but some peaks come from reactions in the detector itself [e.g., 1-3]. Presented here are background peaks from radionuclides made in the high-resolution germanium detectors used for many space missions.

Most early gamma ray spectrometer (GRS) systems used low-resolution scintillators (e.g., NaI), and few peaks were observed in their spectra. Many more peaks are resolved in Ge detectors. Weaker peaks can be identified in Ge detectors, but backgrounds are often more important for many of such weaker peaks. Most Ge detectors in space until recently were used for astrophysics (e.g., HEAO-3 [3]), but now Ge detectors are being used for planetary missions (Mars Odyssey, MESSENGER, and Kaguya-SELENE).

Backgrounds are important for most elements measured by Ge-GRS systems for planetary [1,4] or astrophysical [2,3,5] space missions. Such backgrounds are also seen in Ge-GRS systems flown to near the top of the atmosphere by balloons, in laboratory experiments with energetic particles, and even in low-level counting systems on the Earth's surface.

No peaks are observed from prompt reactions induced by protons because the proton deposits energy in the detector. Fast-neutron inelastic reactions with Ge nuclei make broad, asymmetric peaks when energy from the nucleus' recoil sums with that from a gamma ray [e.g., 1,2]. If the spacecraft is large enough or there are planetary leakage thermal neutrons, narrow peaks are made by Ge(n,γ) reactions [e.g., 1,2].

Many radionuclides are made in Ge detectors. However, no peaks are produced by radionuclides that decay by charged-particle emission (electrons or positrons), as those charged particles deposit a continuum of energy in the Ge. Only decays by an isomeric transition between levels within a nucleus or by the capture of an electron can produce narrow peaks in Ge detectors. The radionuclides that decay by isomeric transition (IT) or electron capture (EC) and produce narrow lines in a Ge detector are discussed here.

Gamma-Ray Peaks from Isomeric Transitions (IT): Usually a nuclear reaction leaves a nucleus in an excited state. If the half-life of that excited level is long enough, its decay will not sum with any energy deposited during the reaction. As most Ge detectors collect charges for ~1 μs, the decay of levels with half-lives longer than ~1 μs can be observed as a peak. Strong background lines in Ge detectors are from the decay of a 20 ms level in ^{71}Ge and from a 48 s level in ^{75}Ge. Such excited levels are considered to be meta stable, and they are identified by the letter m after the mass, such as ^{71m}Ge and ^{75m}Ge. Both reactions induced by fast (~MeV) reactions and the capture of thermalized neutrons can make such radionuclides.

Electron Capture (EC): Often a radionuclide decays by the capture of an orbiting electron. In many cases, both electron capture and positron emission can occur, but only EC decays produced narrow peaks in Ge detectors. In Ge, energetic reactions make many radionuclides that decay by electron capture. Some of the strongest backgrounds from EC decay are from 1.63 day ^{69}Ge, which decays are 76% by EC.

The peaks that result from EC appear at an energy that is the sum of the energy of the gamma ray (or sum of gamma rays) and the binding energy of the electron in the residual nucleus (e.g., ^{69}Ga for ^{69}Ge decay). This sum occurs because electrons replace electron vacancies fast enough that their energies (emitted as X rays or Auger electrons) are summed with the gamma ray's energy.

Most (~85%) of the captured electrons come from the K atomic shell, which have binding energies of ~5-11 keV for residual nuclei from V to As, respectively. Most of the remaining captures are from the L shell (mainly L_1 electrons), which have binding energies of ~1 keV. The ratio of capture for K to L electrons is ~5-10 (and depends on the energies of the neutrinos that accompany EC decay, which are determined by the energy available for the EC decay).

This summing of the electron's binding energy with that of the gamma ray makes identification of EC-produced peaks complicated as the peak is not at the gamma ray's energy.

Sum Peaks from IT or EC Decay: In most cases, the peak is at the energy of the IT transition or the sum of a gamma ray with the electron's binding energy. However, as the decay occurs inside the Ge detector, often the photopeak energies of several gamma rays sum. For example, one of the largest background peaks in Ge detectors, from ^{71m}Ge at 198.39 keV, is the sum of gamma rays at 174.95 and 23.44 keV.

Observed Peaks from Decay in Ge: There are many missions that have observed peaks due to the decay of radionuclides in Ge detectors, such as on Mars Odyssey [1], the International Gamma Ray Astrophysical Laboratory (INTEGRAL) [2], the third High Energy Astronomy Observatory (HEAO-3) [3], and the Transient Gamma-Ray Spectrometer (TGRS) [5]. The stronger background peaks from radionuclide decay in Ge have been observed by most missions with Ge detectors and are given in Table 1. Only a few weak background peaks in spectra from such missions have not been identified [e.g., 1-3,5].

These radionuclides range from ^{44m}Sc made by high-energy reactions to Ge nuclides that can be made by both (n,2n) and (n,γ) reactions with Ge nuclei. Also included are ^{71}As and ^{74}As, which are made only by proton reactions, mainly from energetic protons from the Sun or in the Earth's radiation belts. The half-lives range from 9 μs (which is long enough to be observed) to ~1 year, so the intensity of some peaks depend on the length of time the Ge has been in space.

Cross Sections for Making Radionuclides in Ge: There have been 4 sets of cross sections reported for making radionuclides from Ge with protons up to ~100 MeV [6 and references therein] and one set at 660 MeV [7]. A crude estimate of the intensity of a peak from decay in Ge can be made when the cross sections for making that nuclide are weighted by the approximate energy distribution of nucleons inducing reactions in Ge and then multiplied both by the fraction of the nuclide's EC or IT decay and by the emission probability (Iγ) for the gamma ray. These estimates are generally consistent with the observed intensities of background peaks in Ge from radionuclide decay and show that peaks from radionuclides like $^{56-58}$Co, ^{54}Mn, and ^{44m}Sc can occur in Ge detectors.

Summary: The peaks in Ge detectors from cosmogenic-nuclide decay are well understood. This detailed study helps in identifying backgrounds in Ge detectors, some of which can interfere with peaks of interest.

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References: [1] Evans L. G. et al. (2007) *JGR, 112,* E03S04. [2] Weidenspointner G. et al. (2003) *Astronom. Astrophys., 411,* L113-L116. [3] Wheaton W. A. et al. (1989) *AIP Conf. Proc. 186,* 304-322. [4] Boynton W. V. et al. (2007) *JGR, 112,* E12S99. [5] Weidenspointner G. et al. (2005) *Ap. J. Suppl.,* 156, 69-91. [6] Spahn I. et al. (2007) *Appl. Radiat. Isot., 65,* 1057-1064. [7] Aleksandrov Yu. A. et al. (1991) *Proc. 41st Conf. Nucl. Struct. Minsk,* p. 472.

Table 1. The stronger peaks made in Ge detectors by the decay of radionuclides and their decay properties are listed by energy. A superscript m indicates a meta state that decays by an internal transition (IT). A sum indicates that the peak is the sum of 2 gamma rays. A +K or +L indicates that the peak is the sum of a gamma ray from electron capture (EC) and the electron's binding energy in the residual nucleus.

Peak E (keV)	Isotope	%EC or IT	$T_{1/2}$	Iγ (%)
66.71	^{73m}Ge-sum	100	0.5 s	100
93.31	^{67m}Zn	100	9 μs	100
100.93	^{67}Ga+K	100	3.26 d	3.2
102.97	^{67}Ga+K	100	3.26 d	39.2
119.22	^{66}Ge+K	76	2.3 h	10.4
124.75	^{65}Ga+K	11	15 min	54.0
139.69	^{75m}Ge	100	48 s	38.8
143.58	^{57}Co+K	100	272 d	10.7
159.70	^{77m}Ge	19	53 s	14.0
185.68	^{67}Ga+L	100	3.26 d	21.2
186.05	^{71}As+K	72	2.72 d	82.0
194.24	^{67}Ga+K	100	3.26 d	21.2
198.39	^{71m}Ge-sum	100	20 ms	91.2
271.13	^{44m}Sc	100	2.44 d	98.8
309.88	^{67}Ga+K	100	3.26 d	16.8
392.22	^{66}Ge+K	76	2.3 h	27.9
438.63	^{69m}Zn	100	13.8 h	100
584.54	^{69}Ge+K	76	1.63 d	13.3
606.95	^{74}As+K	37	17.8 d	59.4
817.87	^{58}Co	85	70.9 d	99.4
840.84	^{54}Mn	100	312 d	100
853.88	^{56}Co	81	77.2 d	99.9
882.51	^{69}Ge+K	76	1.63 d	11.9
1040.33	^{66}Ga+L	44	9.5 h	37.0
1048.89	^{66}Ga+K	44	9.5 h	37.0
1078.45	^{68}Ga+L	11	68 min	3.0
1087.01	^{68}Ga+K	11	68 min	3.0
1107.97	^{69}Ge+L	76	1.63 d	36.0
1117.14	^{69}Ge+K	76	1.63 d	36.0
1124.53	^{65}Zn+K	99	244 d	50.6
2199.29	^{66}Ga+K	44	9.5 h	5.6
2761.51	^{66}Ga+K	44	9.5 h	23.3