The physics of gamma/neutron spectroscopy

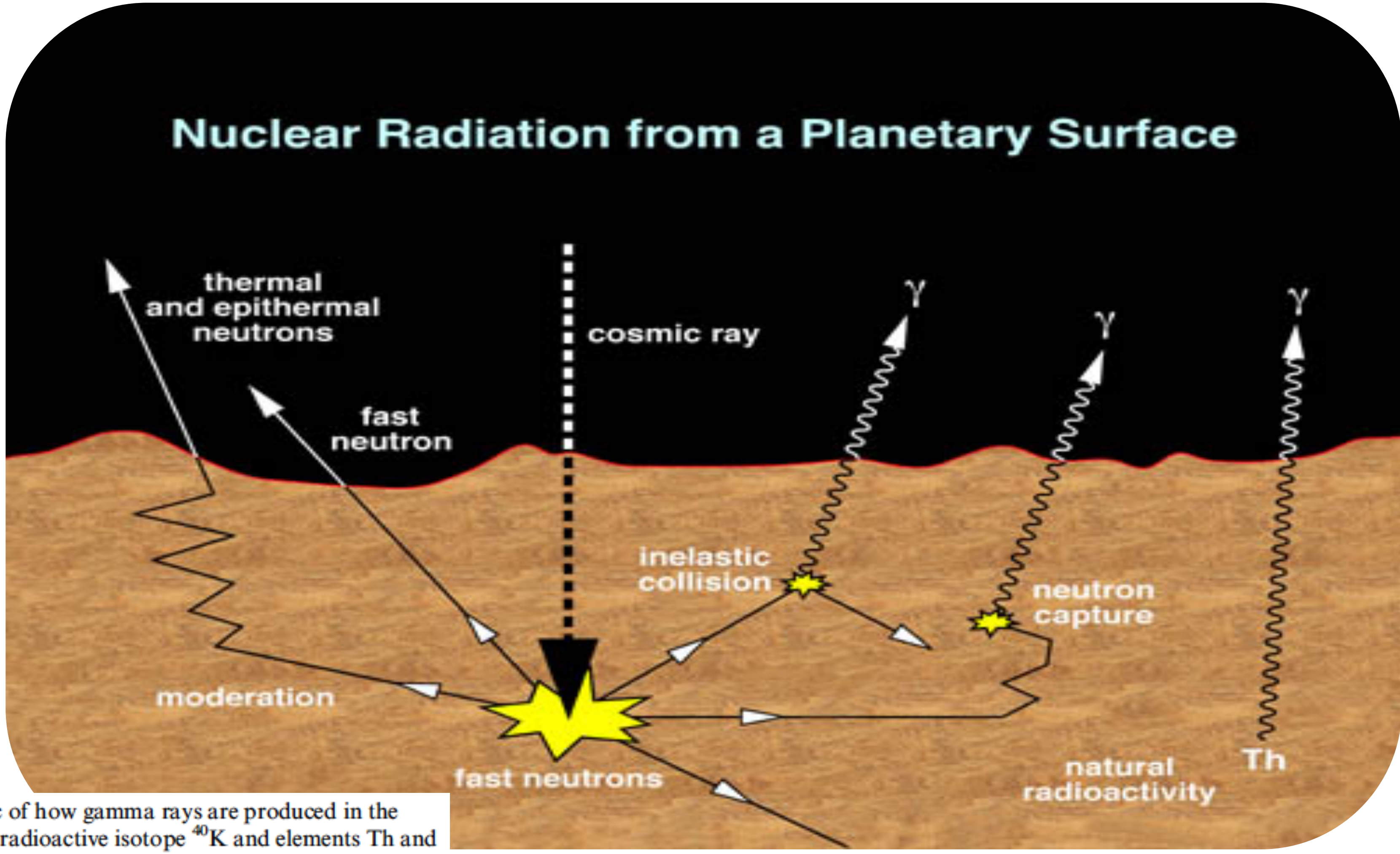


Figure 5.1. Schematic of how gamma rays are produced in the Martian surface. The radioactive isotope ^{40}K and elements Th and U (and their daughter isotopes) produce gamma rays when they decay. The interaction of high-energy (~1–10 GeV) cosmic-ray particles with nuclei in the surface materials produces energetic (fast) neutrons with typical energies of ~1–20 MeV. These fast neutrons can excite elemental nuclei by inelastic-scattering reactions, producing gamma rays. These fast neutrons are moderated by H and other elements, producing slow (thermal, ~0.02 eV) neutrons that can be captured by nuclei and result in the release of gamma rays of specific energies.

Nuclear Remote Sensing

- Background, definitions
- Production mechanisms, elemental sensitivities
- Measurement
- Examples

Background

- Usually used for airless or thin-atmosphered bodies
- Sensitive to elemental/isotopic compositions
- Originate in nuclear transitions

Background (cont'd)

- Energy of photon or particle is most important quantity
  - For gamma rays, energy corresponds to wavelength of photon ($E = h\nu$, or put another way, $E = hc/\lambda$)
  - For neutrons, protons, α particles, etc., energy primarily contained in particle's kinetic energy ($E = mv^2/2$)

- Total Energy is conserved in nuclear interactions

- Typical energies of interest range from "thermal" energies of ~0.02eV up to the 10 GeV (1×10^{10}eV) range

Background (cont'd)

Notation – example reactions:

- ^{16}O absorbs a neutron, ejects a proton, becomes ^{16}N

$$^{16}O(n,p)^{16}N$$

- ^{16}O absorbs a neutron, ejects a lower-energy neutron and a gamma ray, stays ^{16}O. The gamma ray has an energy equal to the difference in energy between the absorbed and ejected neutrons

$$^{16}O(n,n\gamma)^{16}O$$

- ^{16}O absorbs a neutron, ejects an alpha particle and a gamma ray, becomes ^{13}C. Alpha particle has A=4. Since a neutron has A=1, the net change is A=-3.

$$^{16}O(n,\alpha\gamma)^{13}C$$

Production of Neutrons and Gamma Rays

- Cosmic rays consist of very high energy protons and other particles from Sun and elsewhere in the galaxy (more on this on the next slide)

- Free neutrons are produced by cosmic ray interactions with the surface

- Gamma rays are produced by neutrons in the surface exciting the nuclei (which then revert to lower energy states by giving up a photon), or by natural radioactive decay

Cosmic Rays

- Cosmic rays are produced by the Sun and by other sources in the galaxy.

- Cosmic rays are composed primarily of very high energy (0.1 – 10 GeV-range) protons (86%), α particles (13%) and other nuclei with $Z>2$ ($<2\%$).

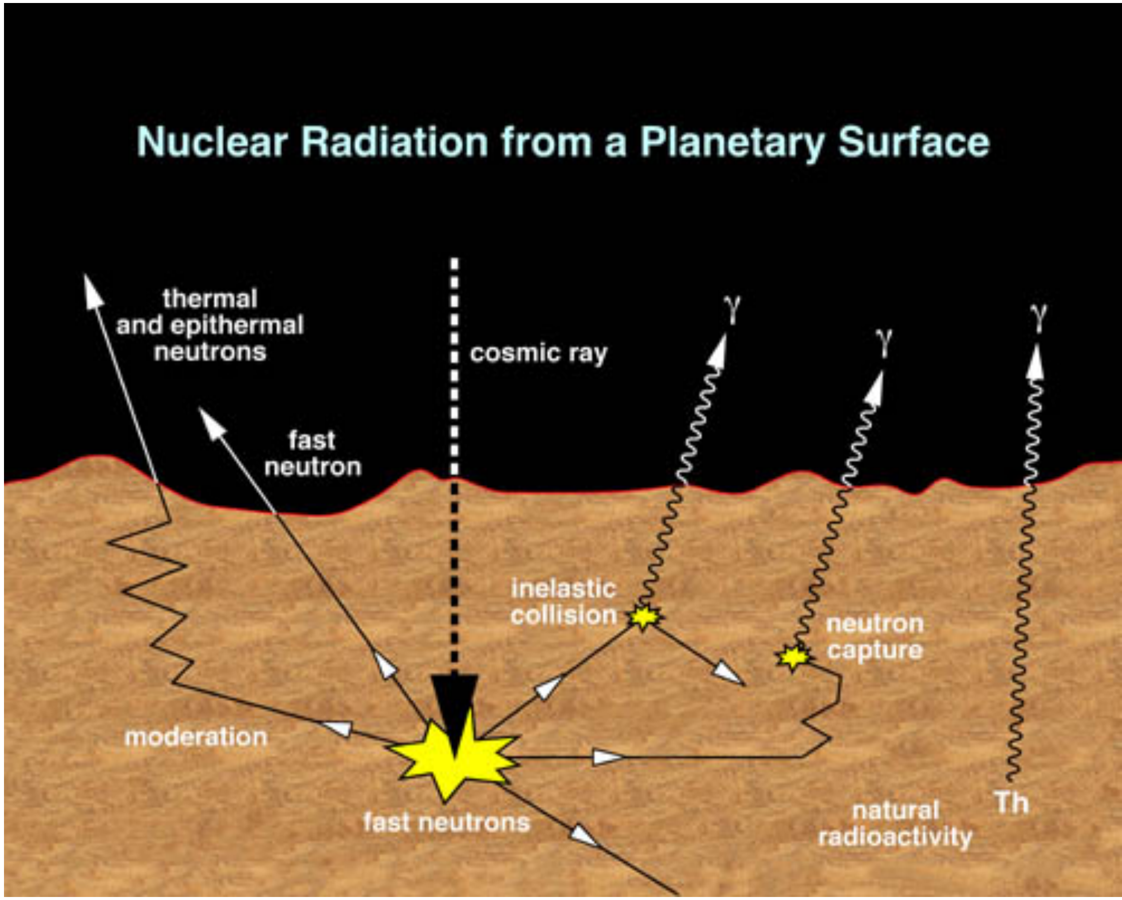
- Cosmic ray flux incident on a planet varies with solar cycles, but averages about 1.5 particles/(cm^2 s)

- Penetration depth in the 10's of g/cm^2. (Note: Earth's atmosphere is about 1000 g/cm^2). Divide by density of surface to get actual depth.

Cosmic rays interact with atmosphere or surface nuclei by *spallation*, which produces fast neutrons in the material (typically ~9 neutrons per cosmic ray particle)

These fast neutrons may:

- Scatter elastically (kinetic energy conserved)
- Scatter non-elastically
  - Inelastic scatter
  - Other non-elastic processes
- Be captured



In the end, all neutrons are either captured, or leak out of the surface and eventually undergo beta decay (mean lifetime ~15 min.)

Elastic Scatter

- Neutron collides with nucleus, kinetic energy is conserved. Leaves nucleus unchanged (in ground state) except for recoil.
  - No gamma ray created

Non-Elastic Scatter: Inelastic Scatter

- When neutron collides with nucleus, some kinetic energy is lost. Nucleus is elevated to an excited state. Nucleus then decays back to ground state by releasing a gamma ray.
  - Incident neutron must have higher energy than excited state of nucleus
  - Example: One $^{56}Fe(n,n\gamma)^{56}Fe$ reaction produces a 0.8467 MeV gamma ray

Other Non-Elastic Scattering

- When neutron collides with nucleus, different nucleus is produced
- Can produce gamma ray directly, and/or product nucleus can undergo radioactive decay and produce a gamma ray
- Examples:

$$^{56}Fe(n,2n\gamma)^{55}Fe$$

$$^{28}Si(n,n\alpha\gamma)^{24}Mg$$

Typical elements that produce gamma rays by non-elastic scattering reactions: C, O, Mg, Al, Si, S, Ca, Ti, Fe

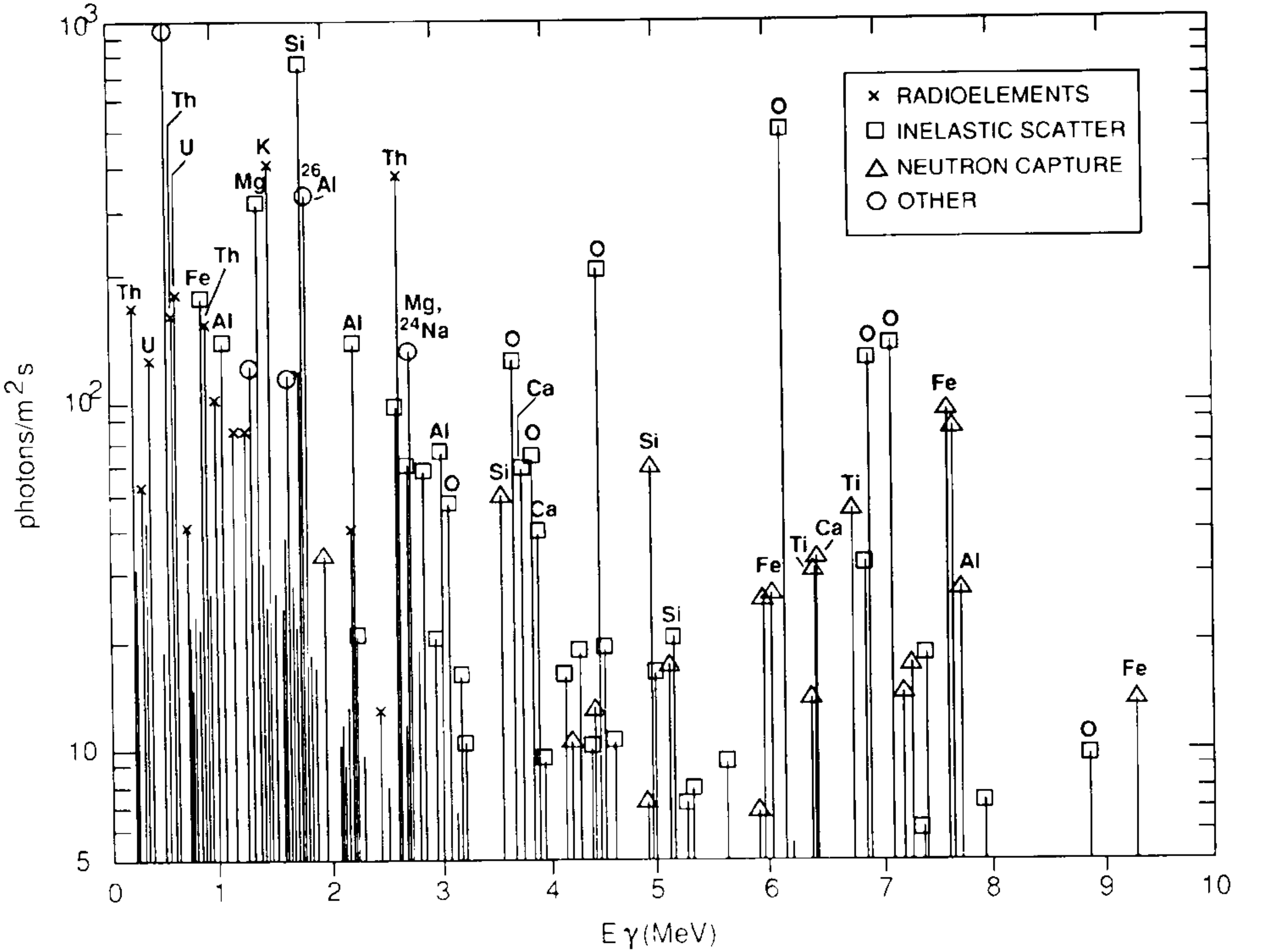
Neutron Capture

- Neutron gets added into nucleus, which is elevated to an excited energy state (but not necessarily one of its normal excited levels).
- Usually, nucleus undergoes prompt de-excitation, producing gamma rays.
- Sometimes produces a longer-lived radioactive nucleus, which subsequently decays and produces gamma rays

Typical elements that produce gamma rays by neutron capture:

H, Al, Si, Cl, Ca, Ti, Cr, Fe, Ni

Gamma Ray Spectra from a Surface



Example: Gamma Rays emerging from the lunar surface

Gamma spectroscopy: element sensitivity

depends on abundance, radioactivity, atmosphere & instrument components (e.g., Mg)

TABLE III

Calculated accumulation times required to achieve 10% percision.

Element	Energy (keV)	Mode	Model Composition	Signal (c/s)	Continuum (c/s)	Time for 10% precision (hr)
H	2223	Capture	0.11%	0.0017	0.24	2400
O	6129	Inelastic	42.3%	0.0223	0.34	20
Mg	1369	Inelastic	5.2%	0.0124	0.37	70
Al	2210	Inelastic	4.2%	0.0029	0.24	820
Al	7724	Capture	4.2%	0.0008	0.25	12000
Si	1779	Inelastic	19.8%	0.0468	0.29	4
Si	3539	Capture	19.8%	0.0035	0.15	370
S	5424	Capture	2.7%	0.0021	0.37	2200
Cl	6111	Capture	0.55%	0.0081	0.34	150
K	1461	Radioactive	0.51%	0.1074	0.35	1
Ca	1943	Capture	4.7%	0.0018	0.27	2300
Mn	7244	Capture	0.4%	0.0009	0.28	9100
Fe	847	Inelastic	17.3%	0.0268	0.59	24
Fe	7632	Capture	17.3%	0.0130	0.26	44
Th	2614	Radioactive	0.30 ppm	0.0037	0.20	430
U	1765	Radioactive	0.078 ppm	0.0011	0.30	6800

Boynton et al. (2004)

Gamma ray spectra

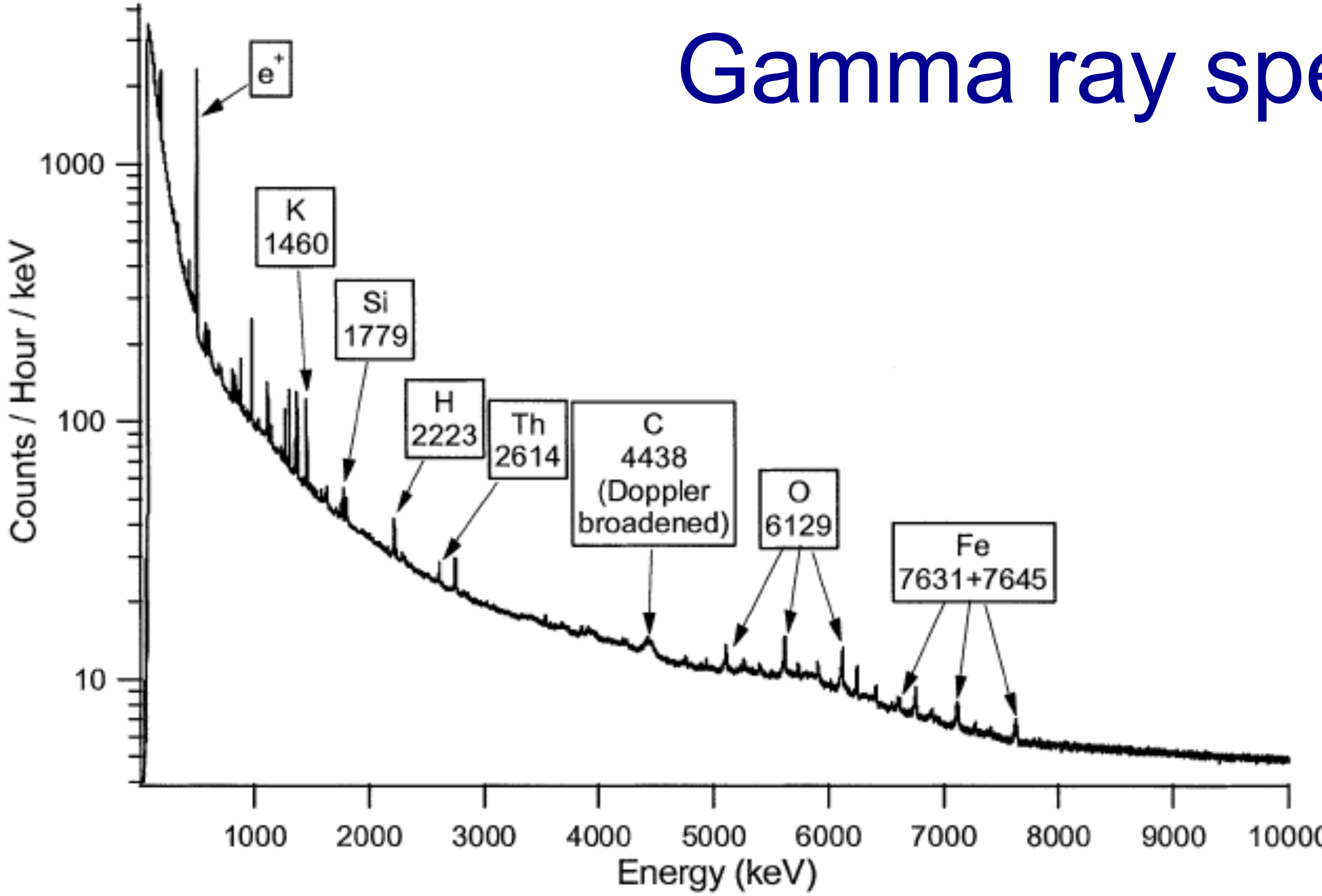


Figure 8. A GS spectrum of Mars taken from June 10 through July 16, 2002. Several emission lines are labeled with their energy in keV and the element responsible for the line. This shows our full-scale energy range of 10 MeV at our nominal gain setting. The continuum above about 8 MeV is due mostly to charged particle interactions in the detector. The broad continuum at lower energies is due mostly to scattered gamma rays that have lost a fraction of their energy. Scattering can occur in the regolith, the atmosphere, or the instrument itself. The line labeled e^+ is due to one of the two 511-keV gamma rays that occur when positrons and electrons annihilate. Positrons are made in one of the processes by which high-energy gamma-rays can interact with matter. The high-energy lines in the spectrum occur in threes, with the lines separated by 511 keV. The lower-energy lines are due to the loss of one or both of the 511 keV gamma rays made when a high-energy photon interacts with the detector via the pair production process.

Boynton et al. (2004)

Gamma ray spectra

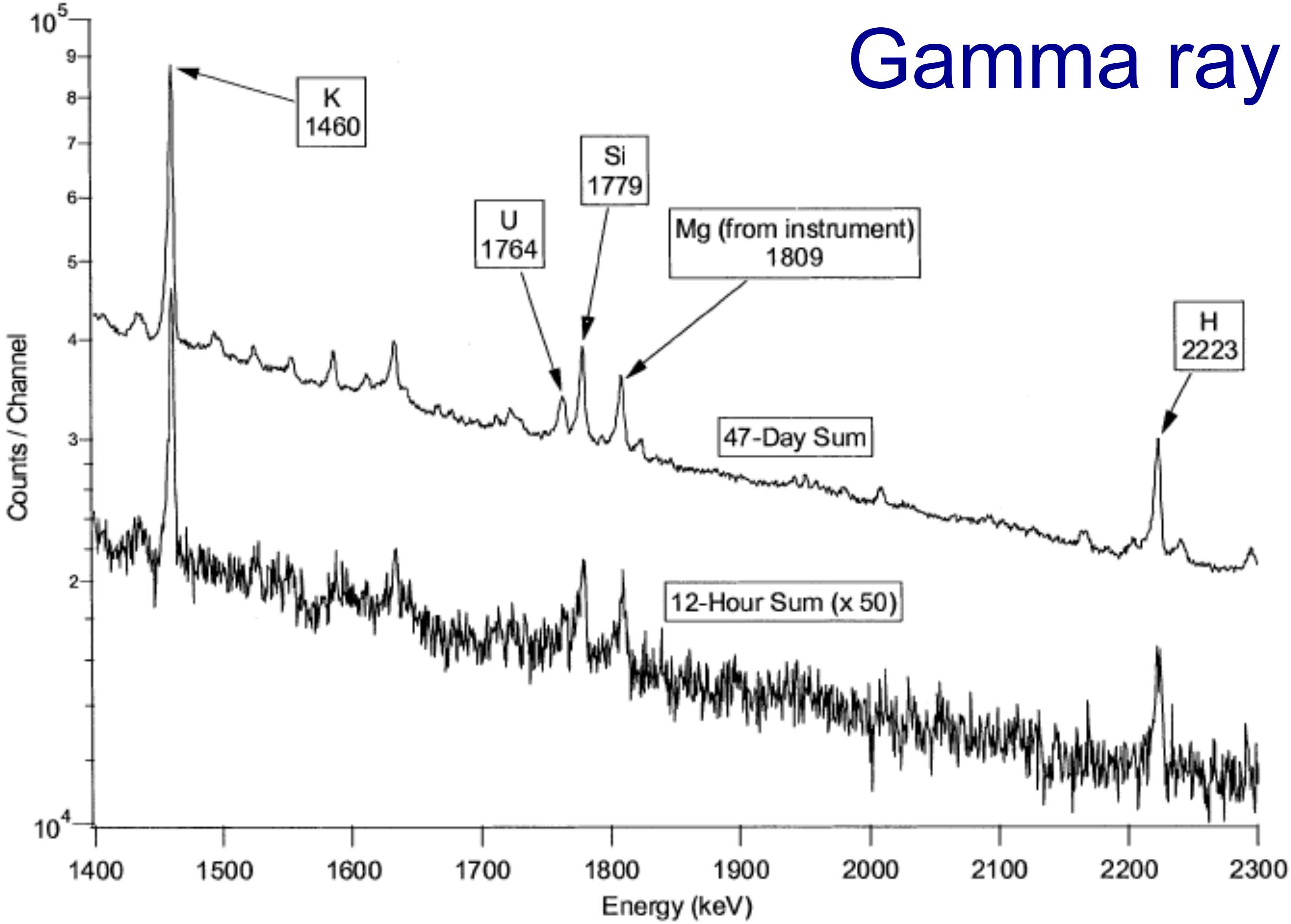


Figure 9. An expanded portion of the full-Mars GS spectrum shown in Figure 8 with a similar spectrum but with a much shorter accumulation time. The nature of the peak shapes can be seen; the area of the peak above the continuum is proportional to the concentration of the element responsible for the gamma-ray emission. The short-duration spectrum, collected for 12 hours, is what is expected for a 450-km footprint at middle latitudes. The uranium line is barely detectable in this spectrum, which shows the importance of being able to sum spectra together over larger regions to improve statistics for weak peaks.

Boynton et al. (2004)

Orbital gamma mapping: ***low*** spatial resolution

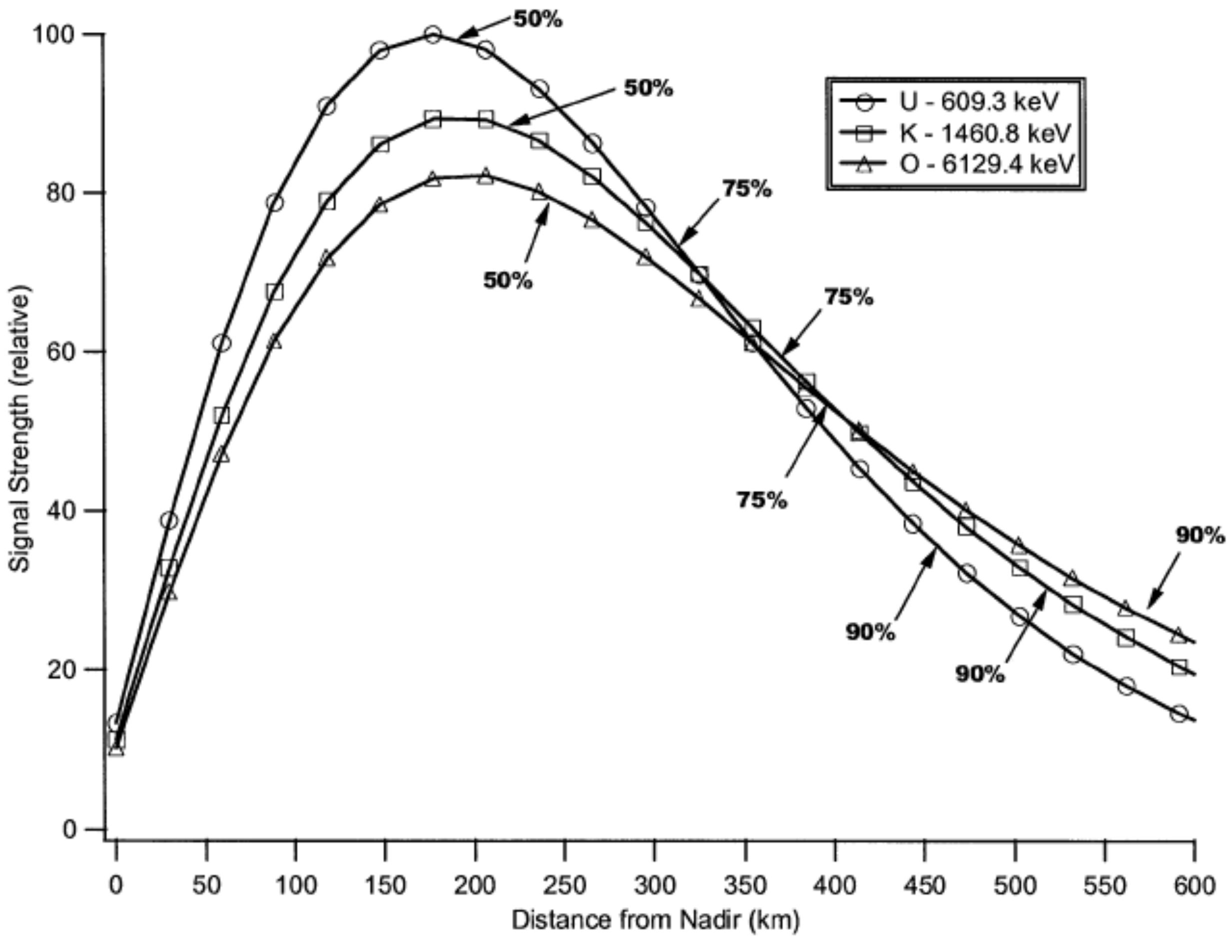


Figure 1. Signal intensity as a function of distance from the sub-spacecraft point (nadir) for three different gamma-ray energies. The signal increases with distance from nadir because the area of each annulus gets bigger, but it then drops off due to attenuation through greater path length through the regolith and atmosphere. The distance is indicated inside of which 50% of the signal is collected. This diagram is generated for a nominal Mars atmospheric thickness of 15 g/cm^2. At low elevations on Mars, where there is a thicker atmosphere, the spot size is smaller, and at higher elevations it is greater.

Boynton et al. (2004)