Space Radiation Dosimetry with the Radiation Assessment Detector (RAD) on the Mars Science Laboratory (MSL)

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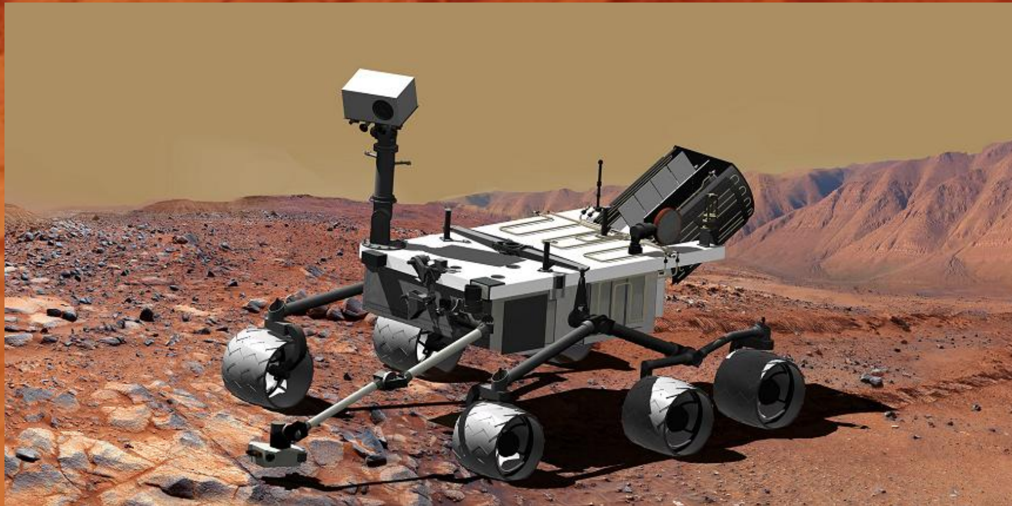
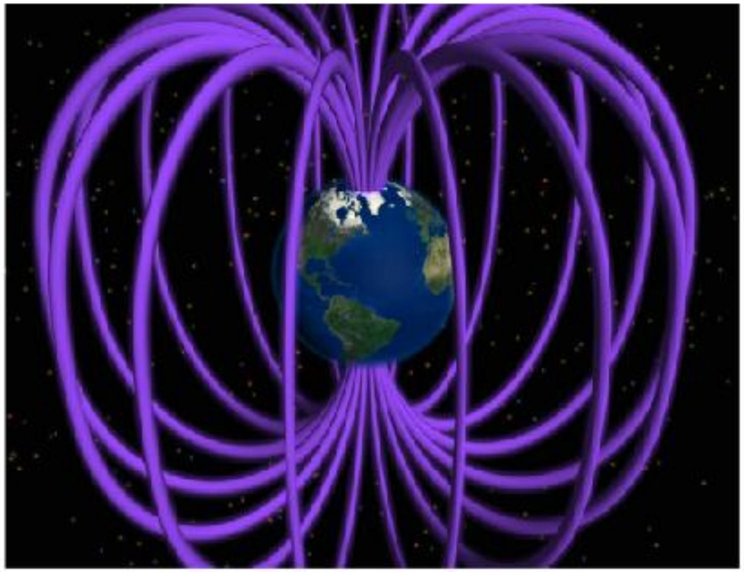
The Mars Science Laboratory (MSL)

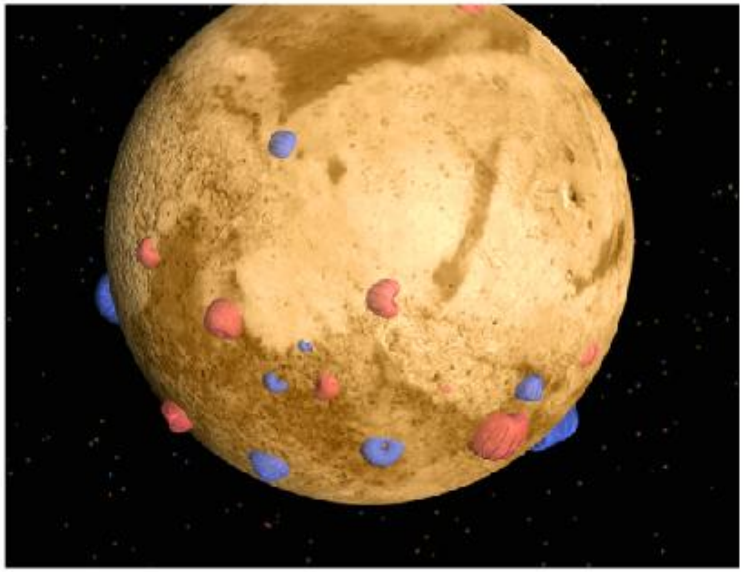
- Launch date is Nov. 2011.
- 10 month cruise phase.
- Arrives at Mars September 2012.
- Prime mission duration is 1 Mars year (687 days).



Radiation Environments on Earth and Mars

RAD – The Radiation Assessment Detector for MSL



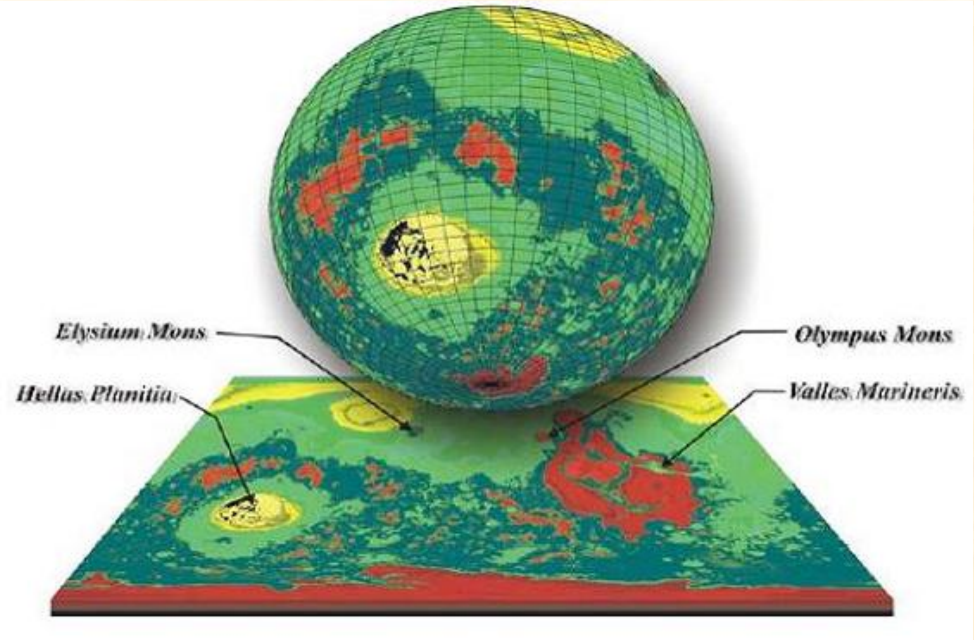


- Martian surface is not well shielded:
  - No planetary magnetic field (just weak local fields).
  - ~ 16 g cm^{-2} of atmosphere vs. ~ 1000 g cm^{-2} on Earth
  - Despite being thin, atmosphere attenuates SEPs & causes a fraction of GCR heavy ions to fragment (e.g., ~ ¼ of Fe survives).

GCR Doses on Mars

RAD – The Radiation Assessment Detector for MSL

- Globe shows calculated skin dose using HZETRN (Saganti & Cucinotta).
  - Surface shielded by the CO_2 atmosphere, varies with altitude.
- GCR doses predicted to be ~1000 times greater on Mars than Earth's surface.
- No data yet – RAD will make first measurements.
- Dose rates are higher in interplanetary space & RAD will also operate while MSL is in cruise to Mars.



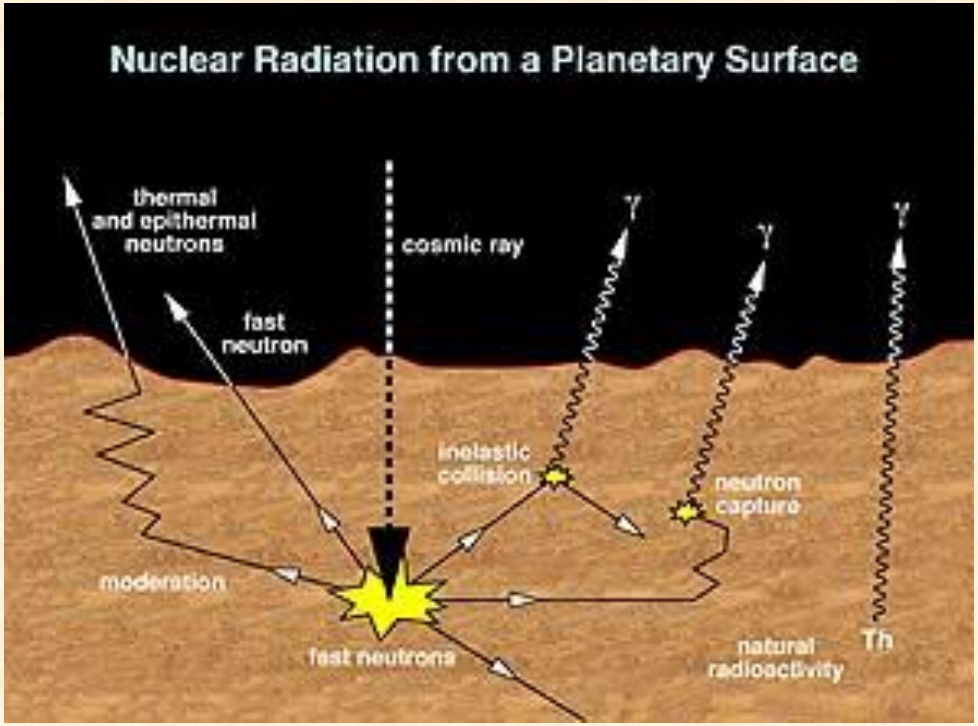
.30	.28	.26	.24	.22	.20

Annual dose-equivalent (Sv/yr)

Neutron Dose on the Surface of Mars

RAD – The Radiation Assessment Detector for MSL

- Secondary particles are created when high-energy GCRs traverse Mars' atmosphere and interact in the soil.
- Interactions of GCRs and SEPs in atmosphere also create neutrons.
- Neutrons may contribute significantly to the dose equivalent on the surface.



RAD Instrument Overview

RAD – The Radiation Assessment Detector for MSL

RAD was selected for MSL to characterize the radiation environment (charged and neutral) on the surface of Mars. RAD consists of:

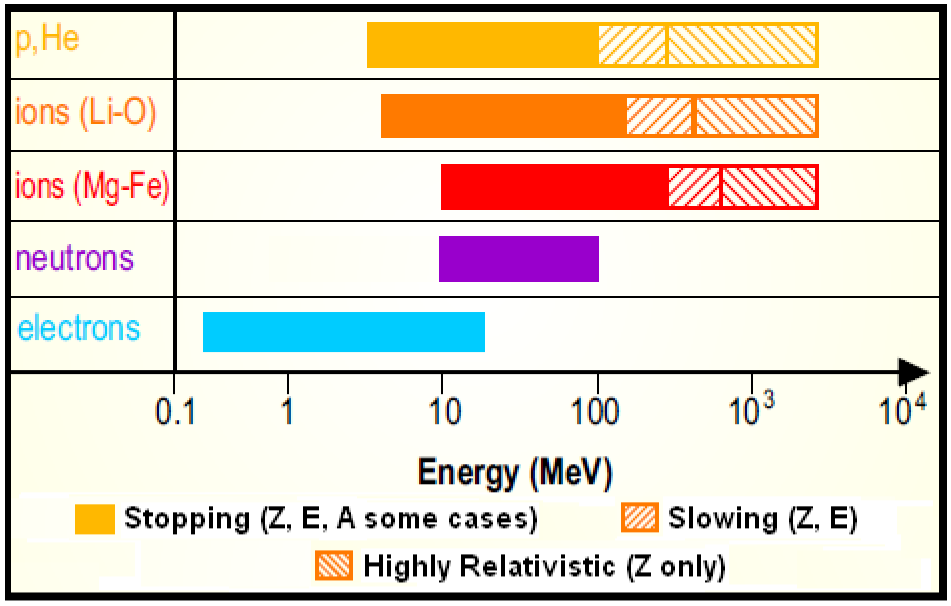
- Solid state detector telescope & CsI calorimeter for charged particles.
- Plastic scintillator w/ anti-coincidence logic to detect neutrons.
  - CsI detects γ-rays also, but RTG background is high.

- Mass = 1.56 kg
- Power = 4.2 W
- Volume = 10 x 12 x 20 cm^3
- Field-of-View = 65 deg. (full angle)
- Geometry Factor = 1 cm^2 sr

RAD Measurement Capability

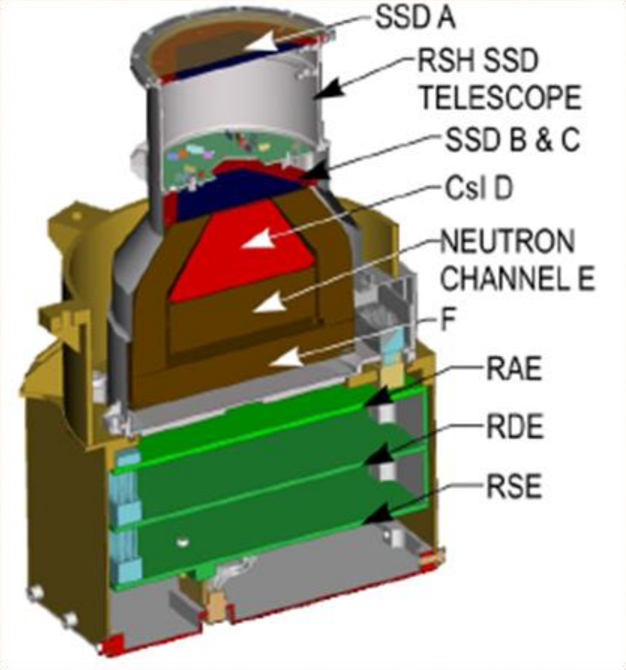
RAD – The Radiation Assessment Detector for MSL

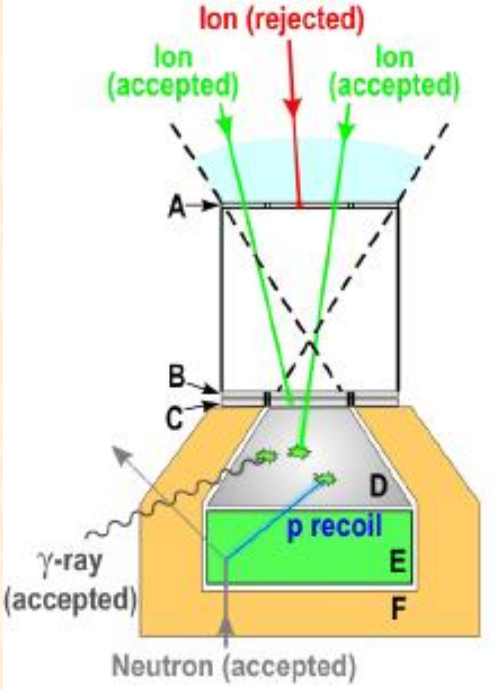
- Charged particles:
  - Protons & heavy ions up to iron can be identified by Z, Z & E, or in a few cases Z, E, & A.
  - Protons up to ~ 100 MeV stop, Fe ions up to ~ 500 MeV/nuc stop.
- Neutrals:
  - Neutrons 10-100 MeV
  - γ-rays > 5 MeV (due to RTG)
- Dose and dose equivalent:
  - Charged – measure LET spectra from 0.2 -1000 keV/μm in H_2O.
  - Neutrons – unfold to get spectra above ~ 10 MeV (large RTG background at lower energies).



RAD Cut-away View and Principle of Operation

RAD – The Radiation Assessment Detector for MSL

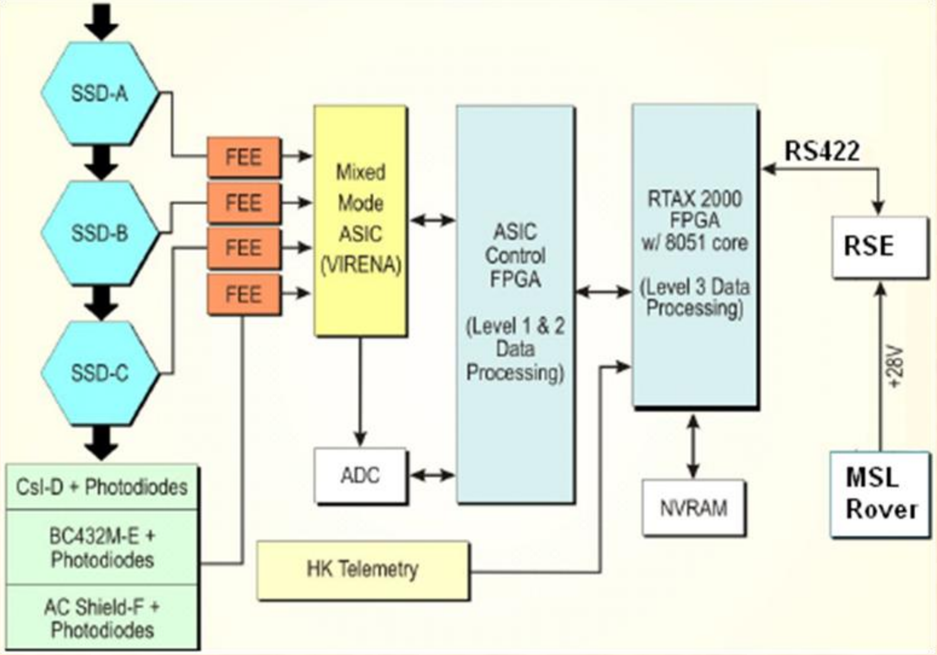




- Thin silicon detectors for dE/dx, CsI for stopping lower-energy protons & ions.
- BC-432 plastic for neutron detection (also stops small % of charged particles).
- Hermetic anticoincidence also made of BC-432.
- D & E each have 3 readout diodes. If γ background is high, these can directly record hits that may appear to have very large energies.

MSL RAD Block Diagram

- RAD Sensor Head (RSH):
  - Detectors & front-end electronics (FEE).
  - FEE have high dynamic range, very low noise.
  - Multiple gain paths for each detector (4 for Si, 6 for scintillators).
- RAD Electronics Box (REB):
  - Custom ASIC (VIRENA) for pulse shaping, discrimination, peak-hold.
  - Over 200 adjustable parameters.



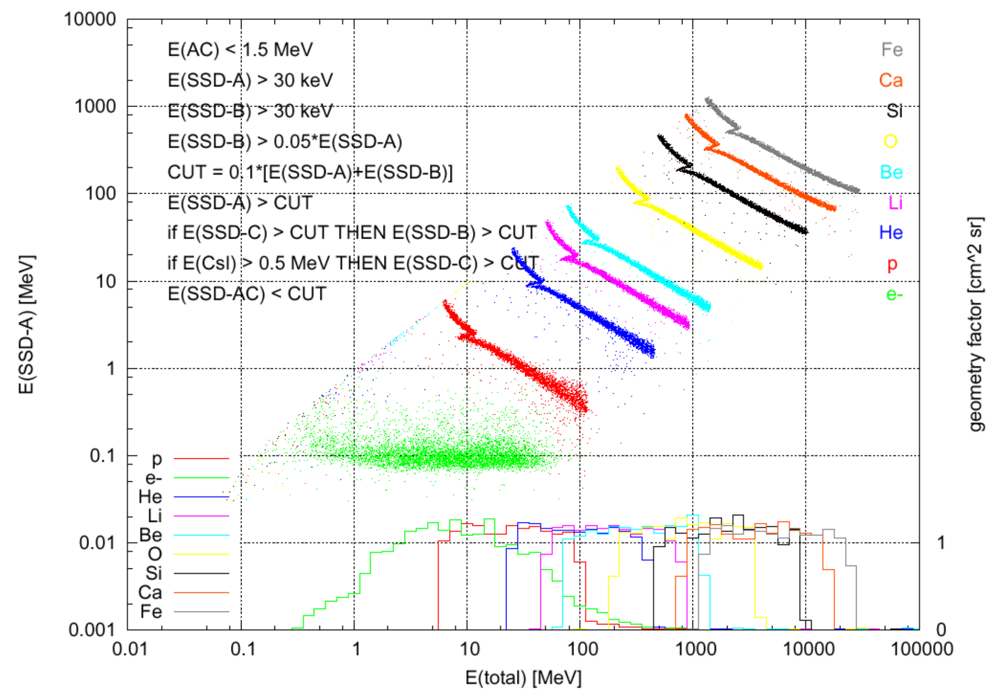
RAD Telemetry

RAD – The Radiation Assessment Detector for MSL

- Telemetered flight data = histograms + event records.
- Event records kept for all high-LET charged particles.
- Low-LET event records sampled due to space limitations.
- The histograms and counter data contain information needed to reconstruct full LET spectra.

Stopping Charged Particles

dE/dx (SSD-A) and geometry factor versus total energy deposit



RAD Calibration Campaigns

RAD – The Radiation Assessment Detector for MSL

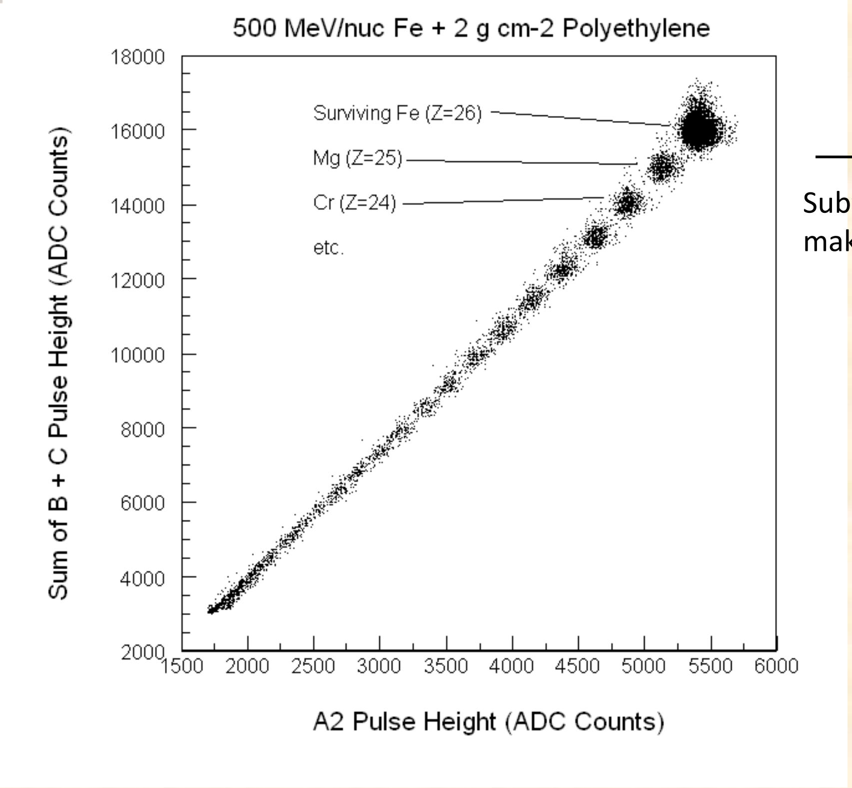
Charged Particles

- NSRL – protons, carbon, iron
- HIMAC – protons, helium, carbon, silicon iron with backup unit in flight-like configuration.
- Sea-level muons
- ^{207}Bi source (electrons up to ~ 1 MeV)

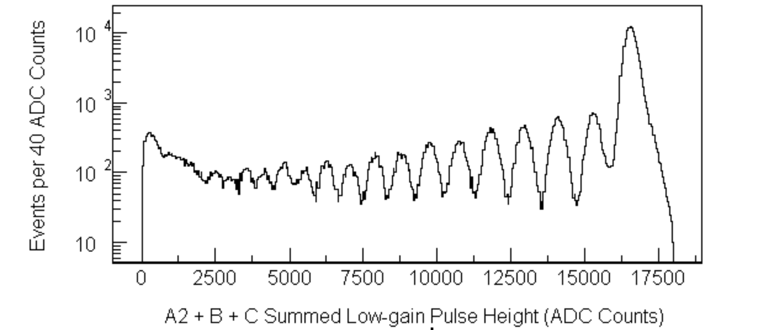
Neutral Particles

- PTB (Braunschweig, Germany) – calibrated neutron beams at 5, 15, 19 Mev
- iThemba – neutrons at 60 & 100 MeV
- NIRS – AmBe calibrated source
- INL – neutrons and gammas from RTG

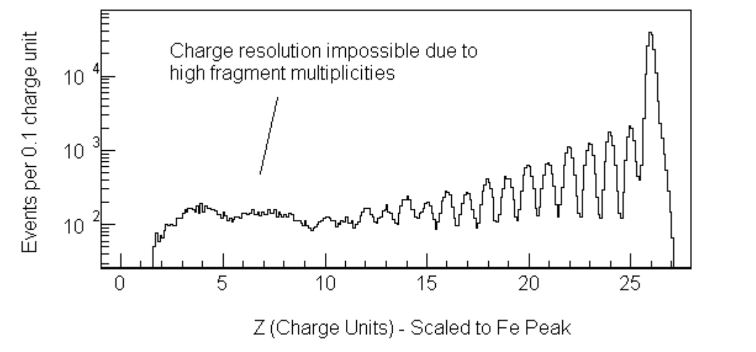
Penetrating Ions in A-B-C



Subtract pedestals, make histogram



Scale to ion charge



- With thin targets, fragments and surviving primaries all have ~ equal velocities, so ΔE in thin detector is ~ Z^2, with well-separated peaks.
- Data shown are from low-gain readout channels. Higher-gain channels pick up the lightest fragments.

Stopping Ions – 500 MeV/nuc ^{56}Fe Data compared to Monte Carlo

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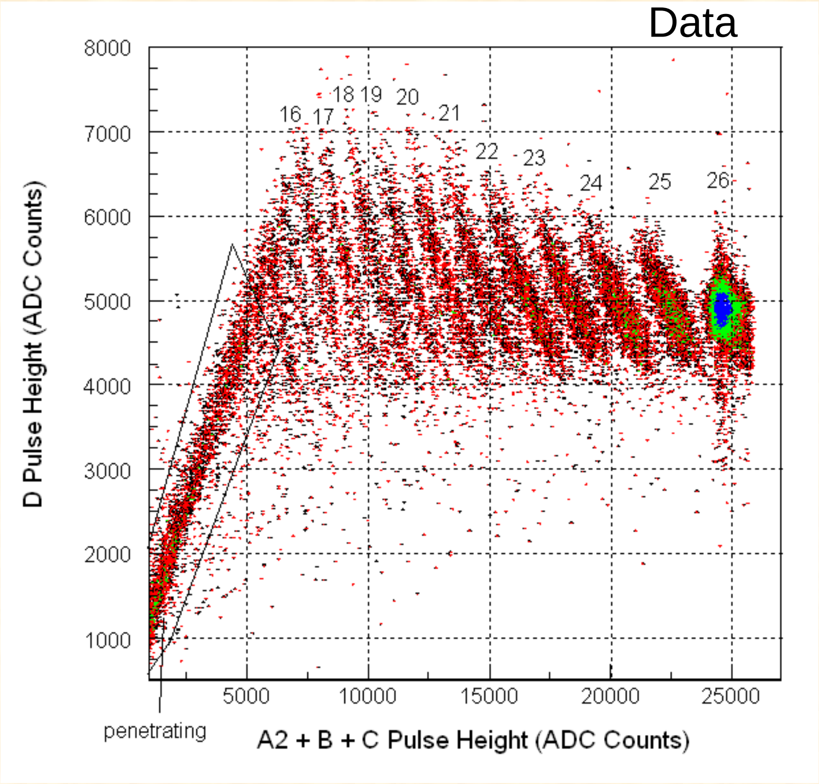

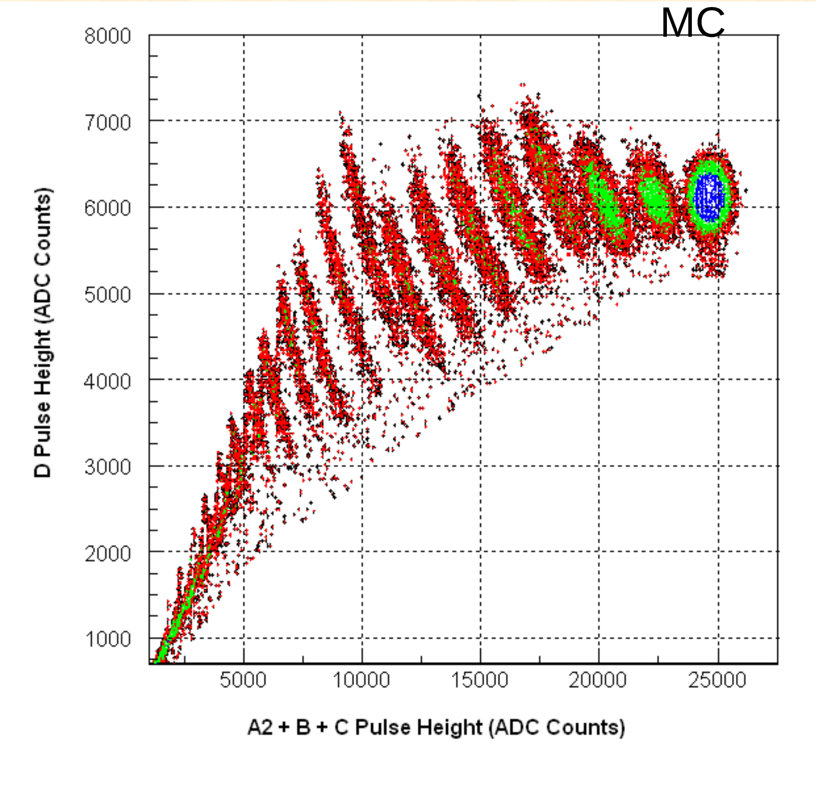

- Monte Carlo lacks quenching in scintillators, see ~ 20% effect for iron & other heavy fragments in the D detector (stopping detector for Fe this run).
- Energy deposited in MC is converted to ADC counts using calibration constants derived from other data sets. MC has perfect resolution.

PTB Neutron Data Analysis and Modeling (O. Kortmann)

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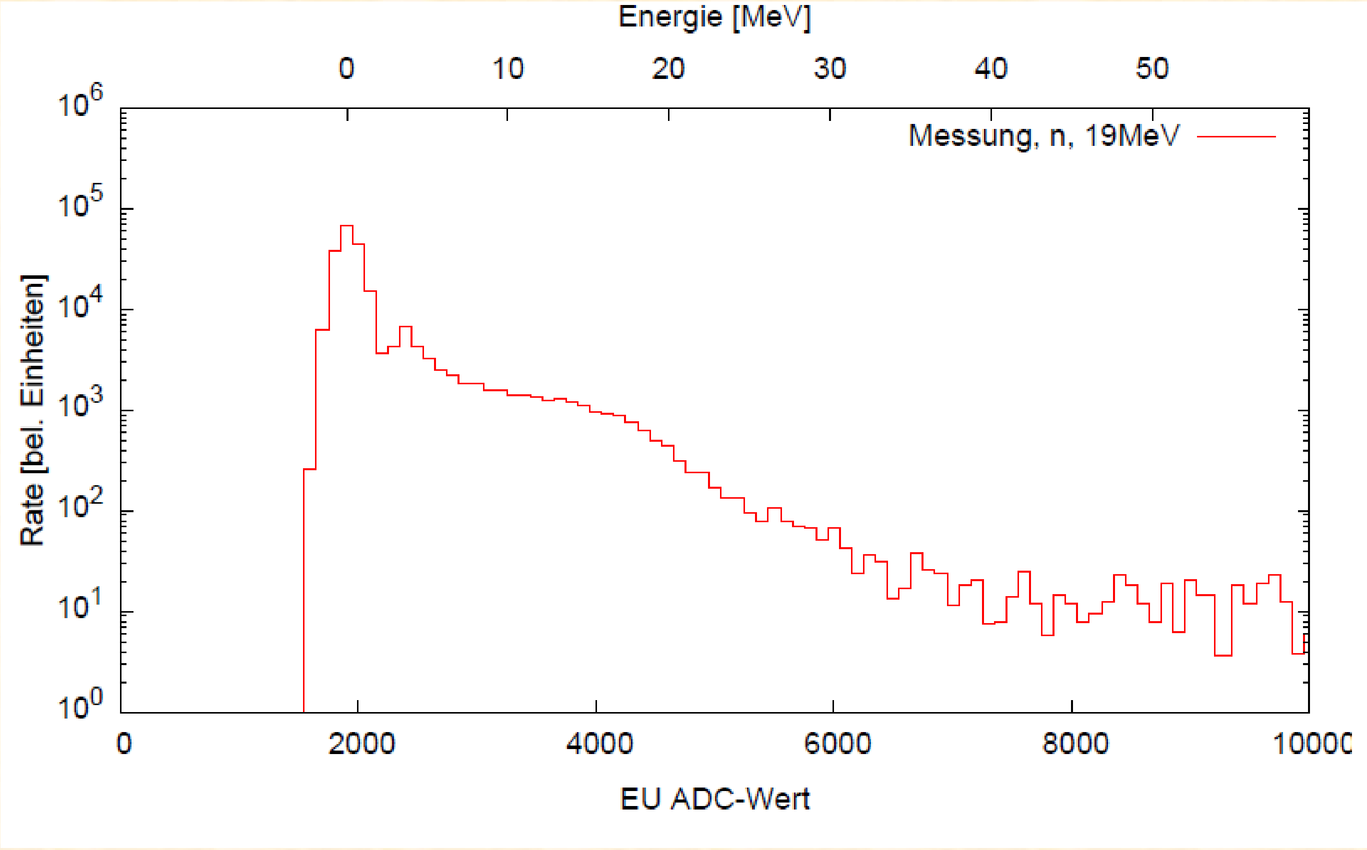

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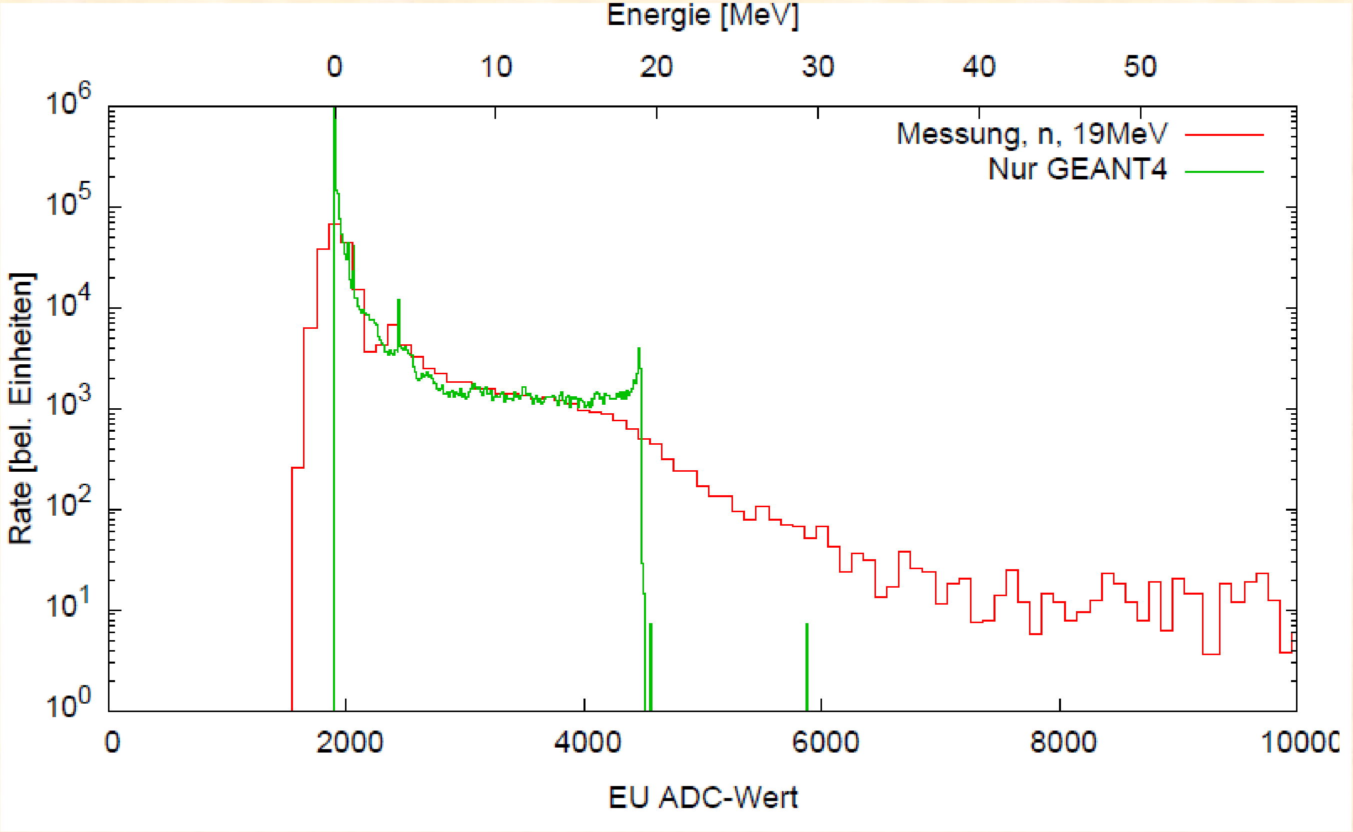

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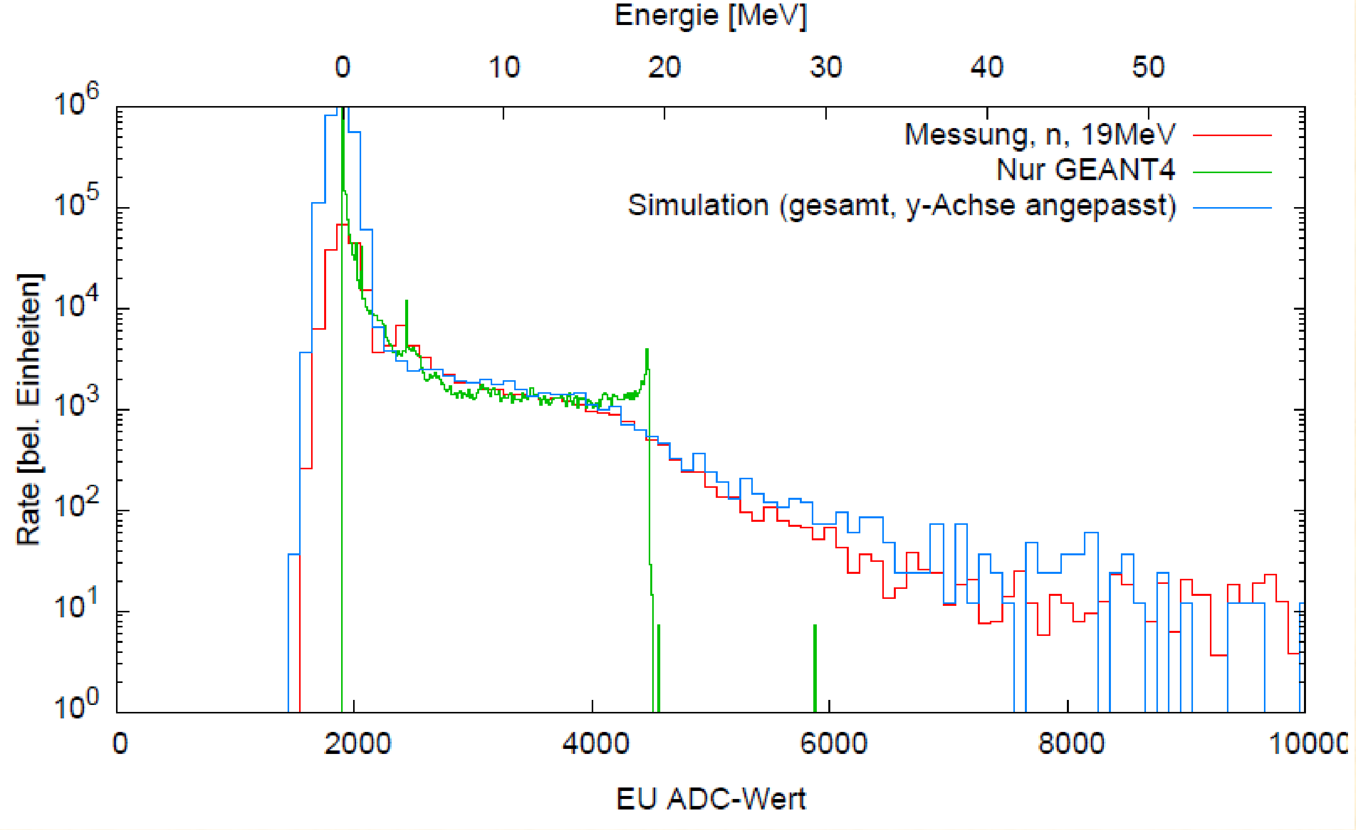
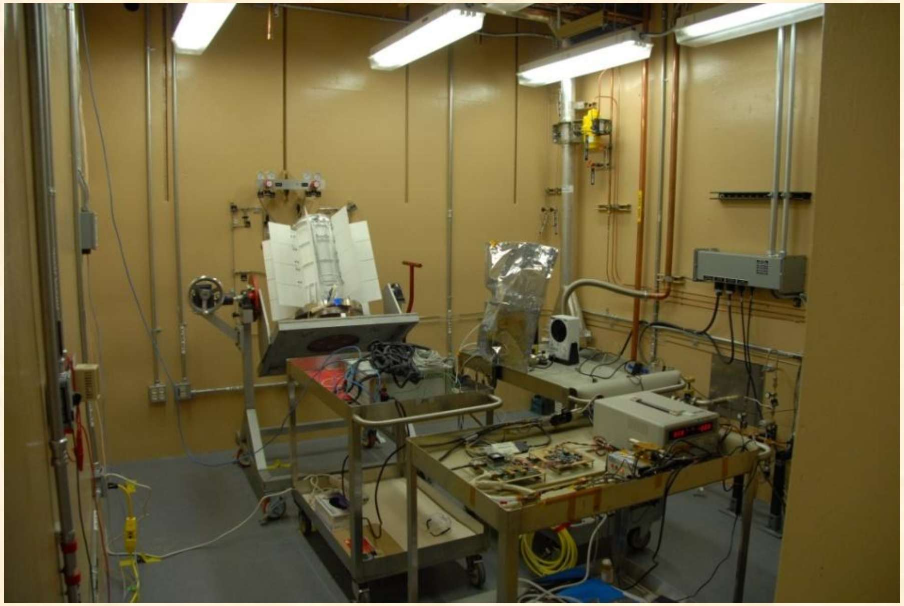


PTB Neutron Data Analysis

- Sharp edge at ADC value corresponding to 19 MeV in GEANT4 Monte Carlo.
- In data, edge not sharp primarily due to unequal sharing of light between the 3 readout diodes.
- We will operate with ~ equal gains on all 3 and combine signals.
- Requiring non-zero energies in at least 2 diodes also reduces RTG background (shown later).
- Quenching accounted for using Birks' formula:

$$dL/dx = \eta \, (dE/dx) / [1 + kB\,(dE/dx) + c(dE/dx)^2]$$

RAD and the MSL RTG



- RAD flight spare taken to Idaho National Laboratory (INL) for test in Feb. 2010.
- Threshold studies with RAD placed 1 m from RTG.
  - RTG is an intense source of γ's & neutrons up to ~14 MeV.
- Large #'s of hits in E and especially D, as expected.
- Goal: adjust thresholds upward until we find tolerable rates (~ 10 Hz).
- Analysis is ongoing but much learned already.

RTG Neutrons and Apparent (But Not Real) Neutrons

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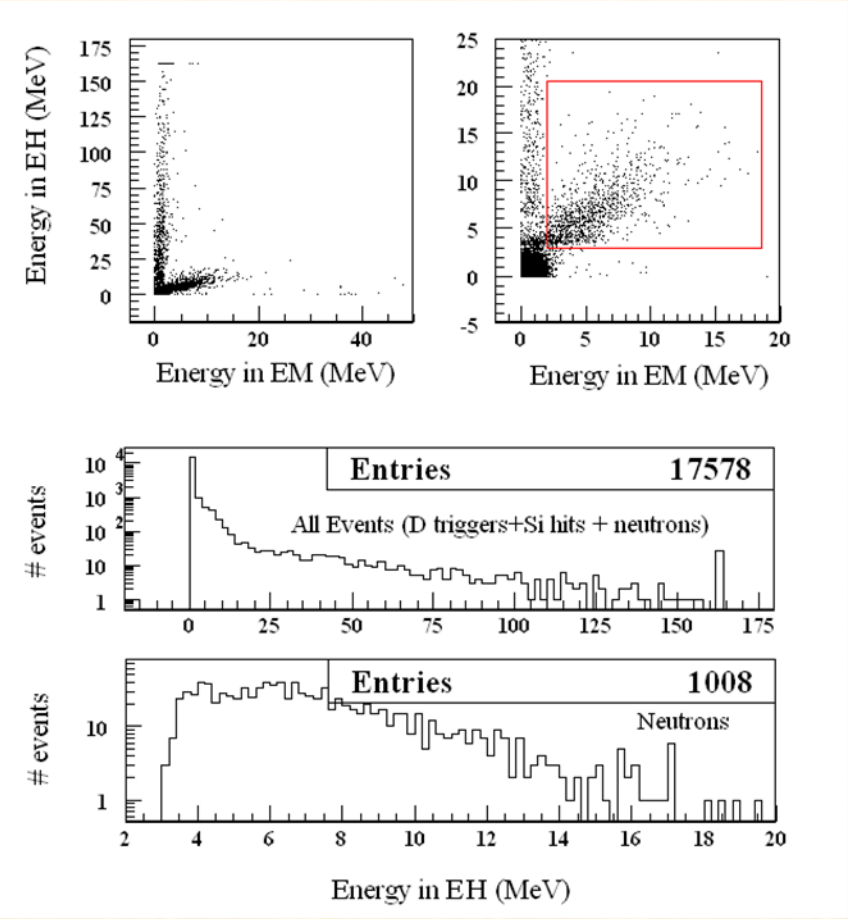

- Some hits in E have impossibly large energy (top-left scatter plot and top histogram).
- There is only energy deposited in 1 of the 3 readout diodes in these events.
- Real neutrons make scintillation light that is shared between the diodes.
  - The large hits must be γ's that hit the diode directly.
- Requiring hits in at least 2 diodes eliminates this background and gives a reasonable ΔE distribution as seen in bottom histogram.

Real-time Dosimetry

- Dosimetry in near real-time from:
  - SSD-B detector → charged particle dose in silicon
  - E detector → charged + neutral particle dose in plastic
- Calculation of charged particle dose using B detector is straightforward.
- Calculation of dose in plastic is more involved.
  - Quenching correction needed.
  - Real-time neutron dose will be a small signal from the environment on top of a large background from RTG.
- More refined dose measurements will require using the entire telescope + inversion to get the neutron spectrum.

Neutron-γ Inversion

- D and E both sensitive to neutrons & γ's.
- Use MC to construct response matrix to be inverted.

$$M := \begin{pmatrix} \mathrm{D-for-}n & \mathrm{D-for-}\gamma \\ \mathrm{E-for-}n & \mathrm{E-for-}\gamma \end{pmatrix} \in \mathbb{R}^{(2m)\times(2m)}$$

$$M \bullet \begin{pmatrix} n(\mathbf{E}_0) \\ \vdots \\ n(\mathbf{E}_m) \\ \gamma(\mathbf{E}_0) \\ \vdots \\ \gamma(\mathbf{E}_m) \end{pmatrix} = \begin{pmatrix} r_D(\mathbf{E}_0) \\ \vdots \\ r_D(\mathbf{E}_m) \\ r_E(\mathbf{E}_0) \\ \vdots \\ r_E(\mathbf{E}_m) \end{pmatrix} \Rightarrow (n(\mathbf{E}_0), \ldots, n(\mathbf{E}_m), \gamma(\mathbf{E}_0), \ldots, \gamma(\mathbf{E}_m))$$

- Inversion constrained by calibration data sets.
  - As always, this is an ill-posed problem and there is no unique solution.

Summary

- RAD will obtain:
  - Charged and neutral particle spectra.
  - Dose measurements.
- Measurements will be the first made on the surface of Mars.
  - Will also measure in interplanetary space during MSL's cruise to Mars.
- Charged particle and neutron calibration data have been obtained, analysis continues with focus on quenching.
- The neutron/γ inversion is being finalized by E. Böhm (CAU-Kiel), appears to work well.
- MSL RAD will meet its mission objectives and will provide the first radiation measurements from the surface of Mars.