Revisiting the Energy Spectrum of Solar Neutrons

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Neutron Monitors

What is a Neutron Monitor?

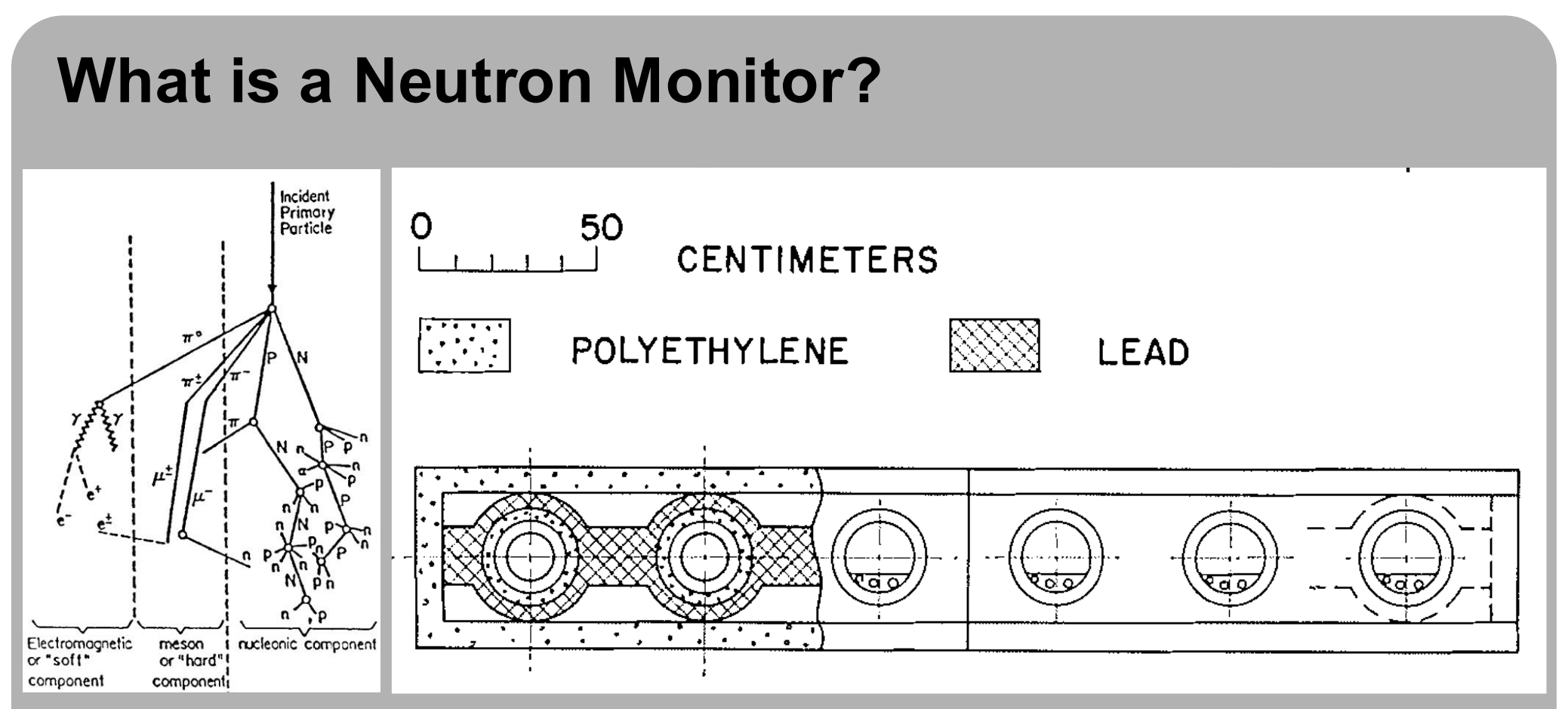

Figure 1. Left – the particles produced in a cosmic ray shower [1]. Right – the components of a neutron monitor [2].

Neutron monitors are ground-based particle detectors that are sensitive to nucleons from cosmic ray showers [1]. When a cosmic ray particle strikes molecules in the atmosphere, it can create secondary particles which can, in turn, create secondary particles of their own. This cascade of particles is known as a cosmic ray shower (figure 1 left).

A neutron monitor consists of several components (figure 1 right). The polyethylene reflector helps prevent background nucleons from the environment from entering the detector. The lead producer and polyethylene moderator increase the chances of detection. Finally, the proportional counter tube "counts" the neutrons that enter it.

The Global Neutron Monitor Network

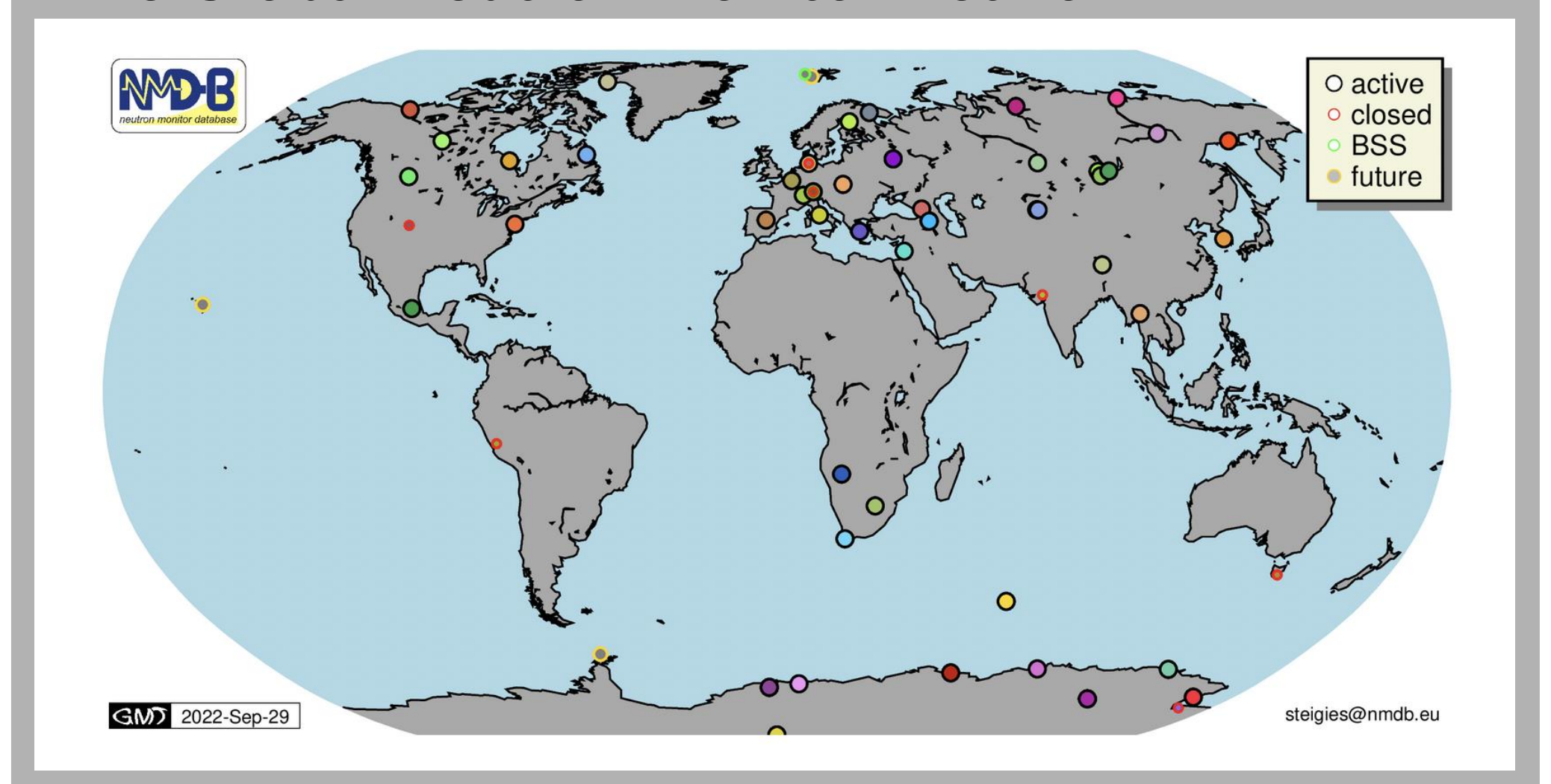

Figure 2. The global neutron monitor network.

The global neutron monitor network consists of ~50 stations distributed around the globe (figure 2). Because of the attenuation of charged particles by the Earth's magnetic field, which varies significantly with geomagnetic latitude and incoming particle direction, each neutron monitor is sensitive to different parts of the cosmic ray spectrum. Because of this, the global neutron monitor network essentially acts a giant spectrometer [3].

UNH Neutron Monitor Stations

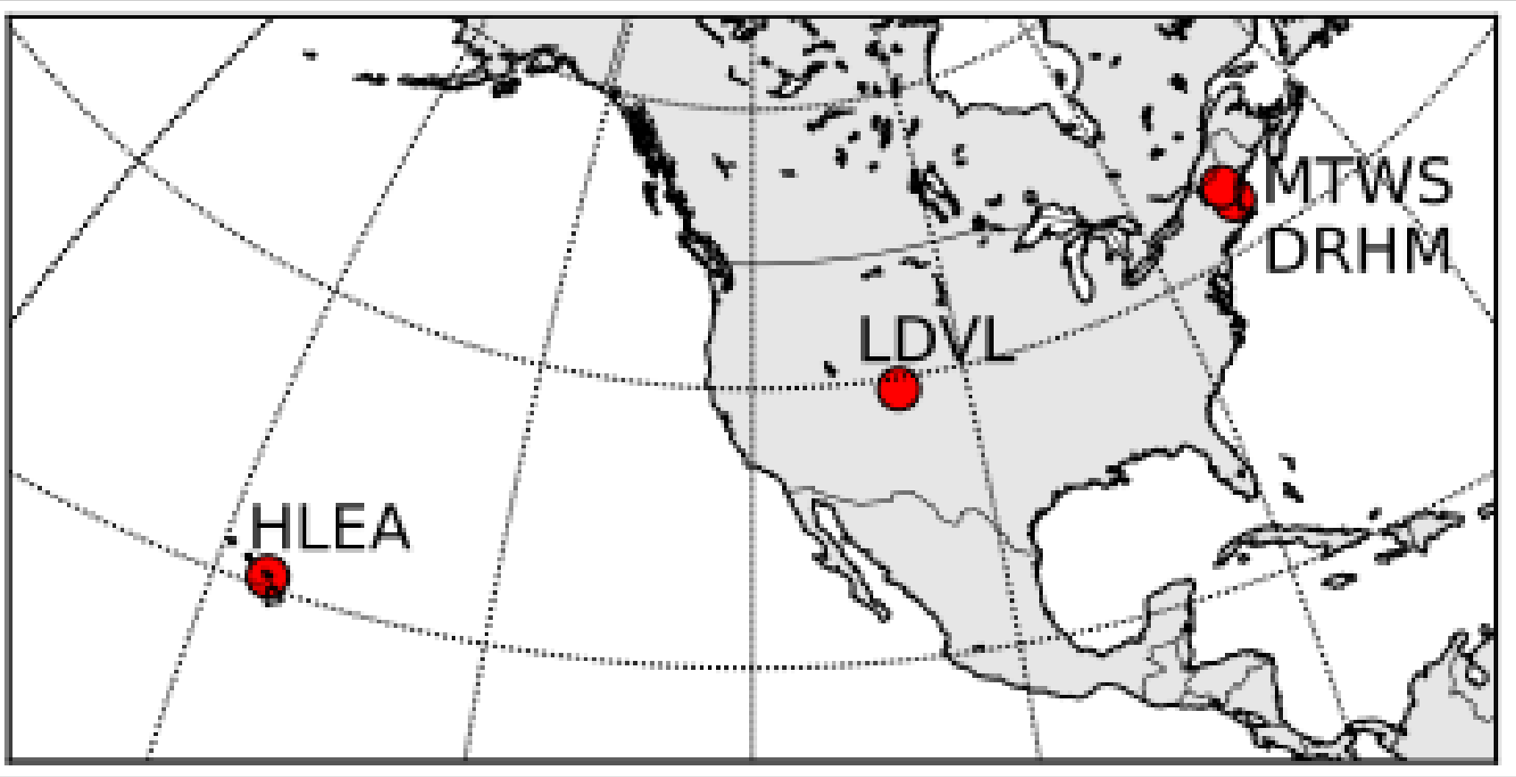

Figure 3. The four UNH neutron monitor stations: Durham, NH; Mt. Washington, NH; Leadville, CO; and Halakalā, HI. The Halakalā station is a collaboration with the University of Hawai'i at Mānoa

Spacecraft

We will get our gamma-ray data from several spacecraft since an instrument is not always observing the sun and not all events will occur within the duration of a single mission.

Figure 4. An illustration of the Fermi Gamma-ray Space Telescope. Credit: NASA's Goddard Space Flight Center/Chris Smith (USRA/GESTAR)

When available, we will use gamma-ray data from the Fermi Gamma-ray Space telescope (Fermi) which has been in operation since 2008 (Figure 4). The primary instrument on Fermi is the Large Area Telescope which can measure gammas in the energy range from 20 MeV to greater than 300 GeV [4]. As needed, we will also utilize gamma-ray data from other spacecraft such as INTEGRAL [5], REHSSI [6] and COMPTEL [7]

What Are Solar Neutrons?

During solar flares, high energy neutrons are produced by accelerated ions in the solar atmosphere. These neutrons carry information about solar energetic particle acceleration and nuclear reactions happening in the solar atmosphere [8]. **If the neutrons are high enough in energy (~250-300 MeV), they will cause particle showers in the Earth's atmosphere that are detected by neutron monitors which are known as "solar neutron events"** [20]. For example, see Figure 5.

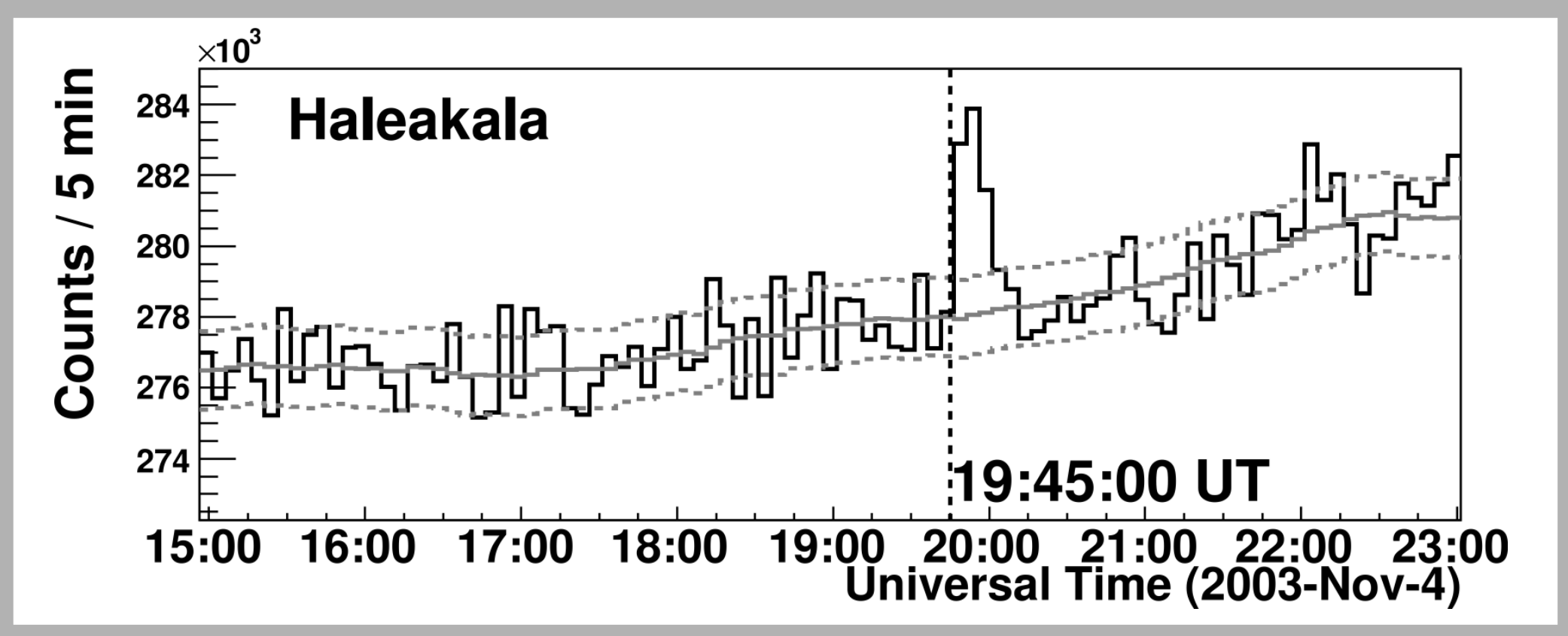

Figure 5. A solar neutron event measured by the Haleakalā neutron monitor in 2003.

Not All Neutron Monitors are Created Equal

Not all neutron monitors stations are equally sensitive to solar neutron events. A station's sensitivity depends on:

- **The detector's location.** A station at low latitude is ideal. Since solar neutrons are not affected by magnetic fields, the response of the detector to solar neutrons is dependent on the solar zenith angle, where an angle closer to vertical is more preferred. This means a tropical location, like that of the Haleakalā monitor in Hawai'i, is a great boon for solar neutron detection [9].
- **The local time and season at the detector.** Local noon around the summer solstice is the most ideal time for solar neutron detection for most monitors. As discussed in the foregoing bullet point, the chances of detection are highest when the sun is directly overhead. For example, the Jungfraujoch neutron monitor in Switzerland, typically poorly located for solar neutrons was able to detect a solar neutron event on June 3, 1982 because it was near local noon, near the summer solstice [10].
- **The detector's altitude.** A station at high altitude is also advantageous for solar neutron detection. The atmosphere attenuates solar neutrons, so the number of observed neutrons increases exponentially with altitude [9].

Why Do We Care?

Because the interplanetary and geomagnetic fields only affect charged particles, neutrons, along with gamma rays, provide direct information about flare regions [11]. The energy spectrum of neutrons released from the sun is highly dependent on the spectrum of ions accelerated in the flares. Solar neutrons help us glean insight into the total number, energy spectrum, time dependence, and angular distribution of ions accelerated in flares. They also provide information on composition, scale height, magnetic field convergence, and magnetohydrodynamic turbulence in the flare region. [12]

Neutron Producing Flares

The plot shown in Figure 7 is from the first confirmed solar neutron event on June 3, 1982 and is characteristic of the high energy (> 25 MeV) neutral radiation from a flare that results in a solar neutron event on the ground [10]. The first peak (lower plot, 11:43) is called the "impulsive phase" and due to photons. The second peak (lower plot, 11:45) is called the "extended phase", has a significant neutron component, and can last for many minutes to hours [10] [14] [15]. The extended phase is also rich in pion decay radiation, unlike the impulsive phase [16]. It is worth noting that lower energy radiation (top plot), such as x-ray and order MeV gamma, returns to pre-flare levels (or significantly decreases) during the extended phase, unlike the higher energy radiation. Not shown, the Jungfraujoch neutron monitor began detecting a neutron monitor event at ~11:45 which lasted until at least 11:55.

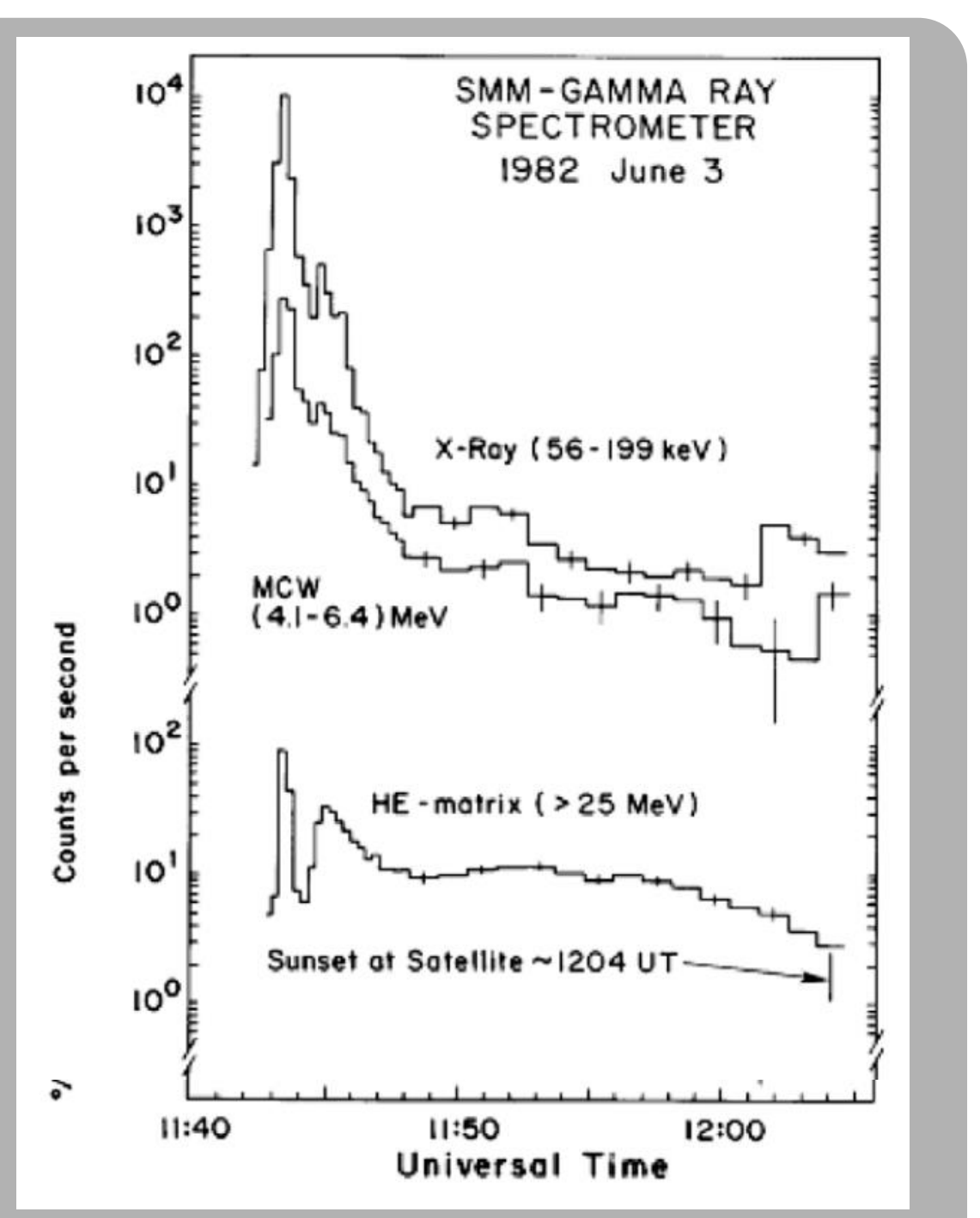

Figure 7. Neutral radiation from the solar neutron event on June 3, 1982. In the lower plot, the first "impulsive" peak is from photons and the second "extended" peak is from neutrons. [10]

What Do Gammas Tell Us?

There are several indicators of nuclear reactions during flares in the gamma ray spectrum, some of which are shown in Figure 6 [13][17]. The presence of neutrons is indicated by the 2.223 MeV neutron capture line. Excited carbon and oxygen nuclei produce lines at 4.4 and 6.1 MeV, respectively. Higher energy reactions can produce pions if they are above the pion production threshold. Positrons that originated from charged pion decay (not shown in Figure) or decay of radioactive nuclei (shown) annihilate with electrons to produce a peak at 0.511 MeV. **Neutral pions decay rapidly into gammas which results in a "peak" at 67 MeV (not shown in Figure) which is flat and wide as a result of doppler broadening.**

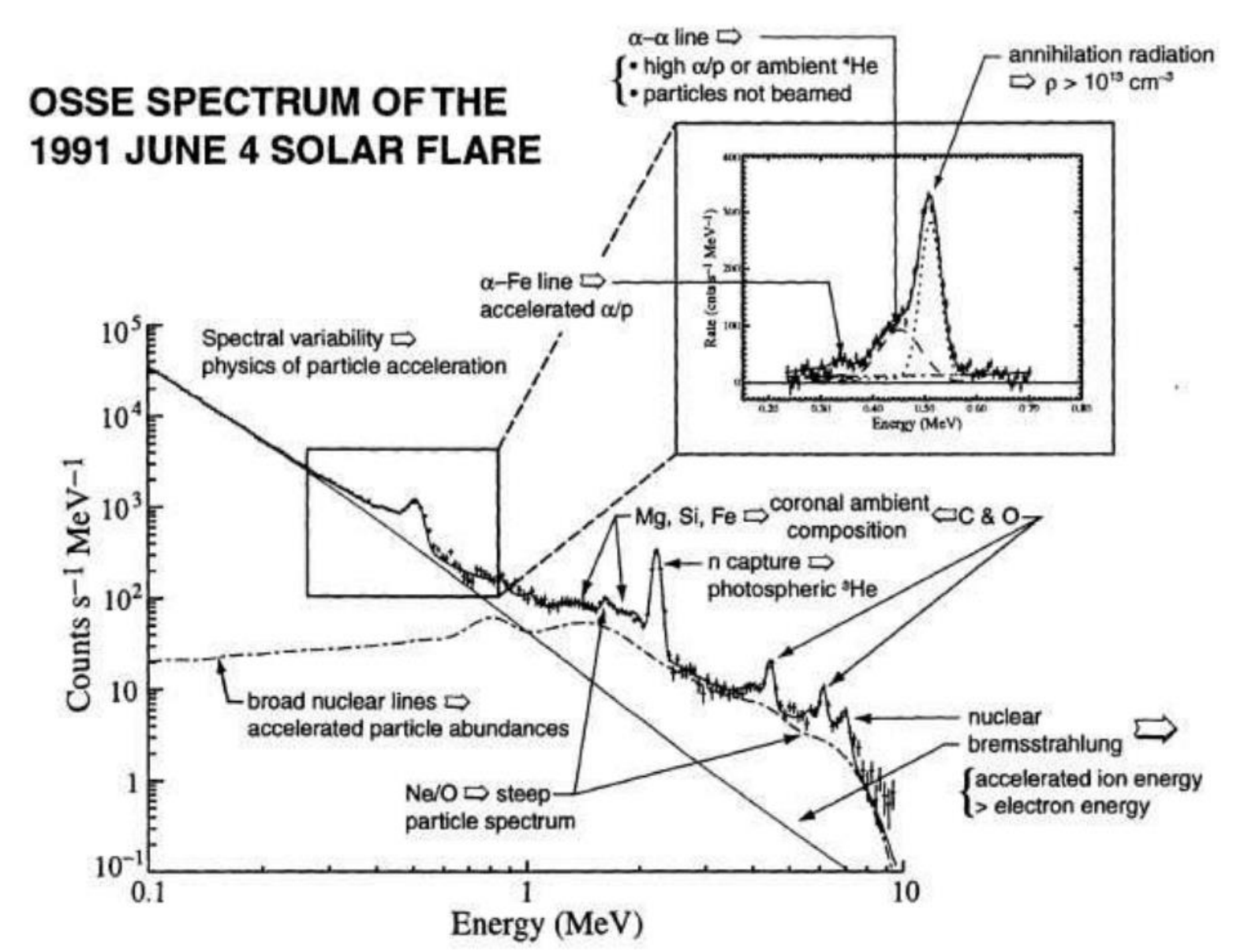

Figure 6. The gamma ray spectrum from the impulsive phase of a flare on June 4, 1991. Seen in the figure are 2.223 MeV line from neutron capture, the 4.4 and 6.1 MeV lines from excited nuclei, and the 0.511 MeV peak from positron-electron annihilation [17]

Three Critical Facts

1) **The neutron energy spectrum can be determined empirically with a time-of-flight method which depends critically on the time which neutrons are released from the sun.** Because the neutron release time is not known directly from measurement, features in gamma radiation are used as a proxy [19].
2) **Ions in the sun with the energies required to cause a solar neutron event on the ground will also produce pion decay gammas.** This is because threshold energy for pion production is ~300 MeV in the rest frame of the solar atmosphere, roughly the same as the energy required by neutrons for detection on the ground [20].
3) **Gammas from pion producing reactions are found during the extended phase of the flare, not the impulsive phase [13] [16].** We believe pion decay gammas in the extended phase are a better proxy for the neutron release time than the gammas from impulsive phase

Future Investigations

Chupp and Ryan [18] and Ajello et al [15] have identified 7 and 37 flares respectively, for a total of at least 42 events which potentially meet the criteria for high energy neutron production. We will utilize gamma ray data from spacecraft and neutron data from neutron monitors on the ground to calculate the energy spectrum of solar neutrons for as many of the events as possible.

Past Investigations

Earlier studies (performed before many flares with an extended phase were on record) assumed that neutrons were released during the impulsive phase of the flare because high fluxes at 2.223 MeV, 4.4 MeV, and 6.1 MeV during the impulsive phase, see for example [19]. Although this is certainly evidence of neutron production, the energies involved can be much lower than the ~300 MeV required for a solar neutron event on the ground [12].

It is likely that in our future investigations that the neutron spectrum will be calculated to be much harder than in previous studies since neutrons released during the extended phase of the flare instead of the impulsive phase would have to travel to earth on the order of a couple of minutes faster. For example, a time offset of one minute would misinterpret a 1 GeV neutron as a 0.6 GeV neutron.

Acknowledgements

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