Solar Flare Neutron Measurements for the Upcoming and Following Solar Maxima

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Solar Neutron Science

High Energy Solar Physics

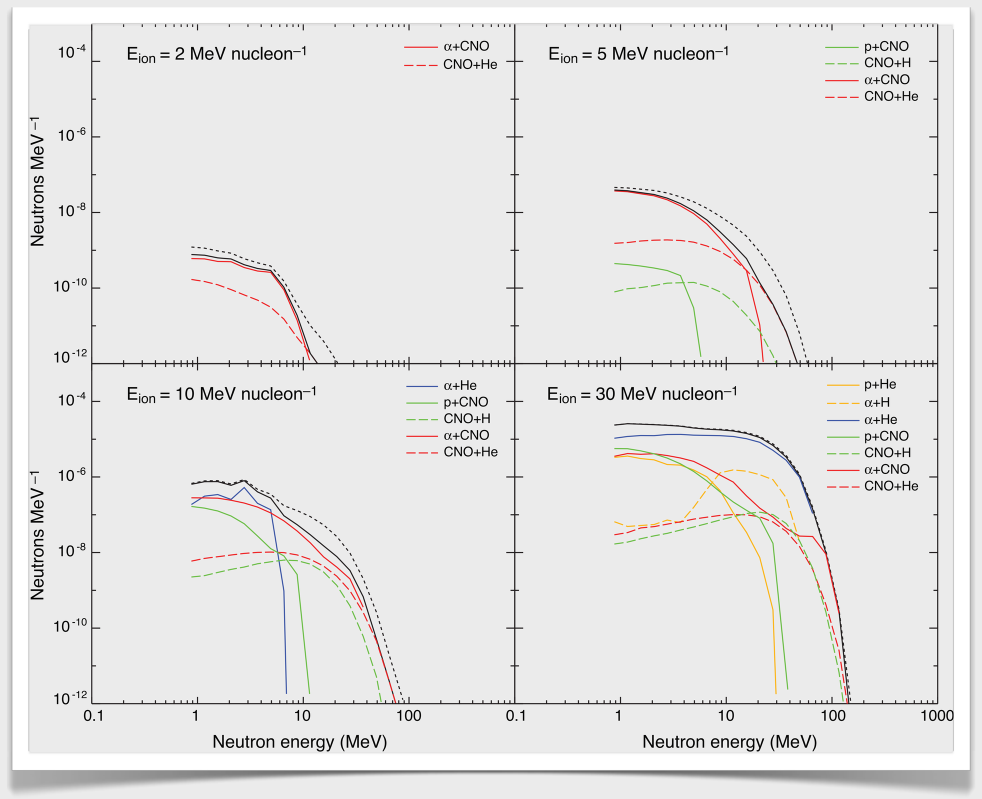
- The only way to study high-energy solar phenomena ***in flares*** is by way of measuring the emitted γ rays and neutrons. These neutral particles are produced in relatively dense media and then can freely escape. The origin of charged particles detected in space is still uncertain, especially at the highest energies. Most, if not all, are accelerated by interplanetary processes.
- Gamma-ray instruments, most recently RHESSI, have flown in space for decades and have revolutionized our understanding of high-energy solar physics.
- Some instruments have been sensitive to neutrons, in particular the Gamma Ray Spectrometer on the Solar Maximum Mission and OSSE on the Compton Observatory.
- Only COMPTEL on the Compton Observatory has performed neutron spectroscopy on solar flare neutrons, and then only for a few intense and select events from 20 years ago this month.

Some Basics

- The neutron lifetime is of order 900 s.
- Few neutrons at 1 MeV (1:10^{-6}) reach Earth orbit.
- Measurements at Earth orbit restricted to >10 MeV
- Below 100 MeV, mostly produced by spallation from heavy nuclei reactions
- Above 200 MeV, associated with pion production and high energy γ rays.
- Neutrons thermalize in the photosphere and produce 2.223 MeV γ rays.
- Neutron backgrounds are ubiquitous and intense around Earth.

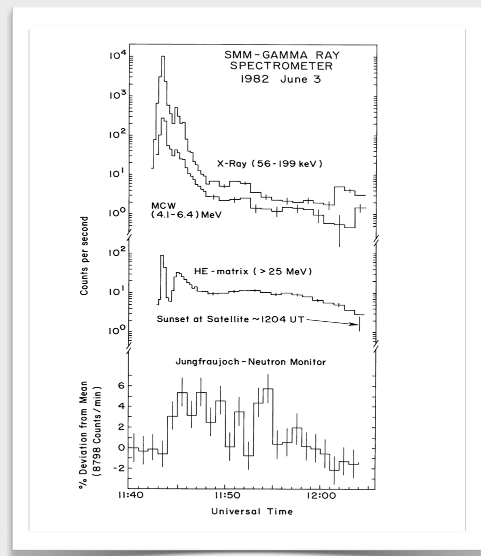
If we already measure γ rays, why measure neutrons?

- Gamma ray lines collapse the energy range of the accelerated protons and/or ions (protons for short) into a single spectral feature. This integration effect enhances the signal, but erases the proton spectral information. Multiple lines must be employed to deduce the proton spectrum.
- Gamma-ray cross sections peak in the 10-30 MeV range, and with a decreasing proton spectrum (e.g., power law) most of the γ-ray signal comes from the narrow 10-30 MeV range in the proton spectrum.
- Spallation neutrons follow the energies of the parent protons, so selecting a neutron energy range samples a particular proton energy range.
- Neutron production cross sections span a wide range of energies and are preferentially sensitive to nuclei heavier than hydrogen in both the beam and the target.
- Low-energy neutron production is described in the figure below. Note that 10 MeV neutrons can be produced by 2 or 5 MeV protons or ions. This takes places in exothermic reactions with neutron-rich nuclei, such as ^{13}C.



Neutron production spectra from monoenergetic ions for various reaction channels. The isotopic composition is assumed to be solar-like, including neutron-rich nuclei.

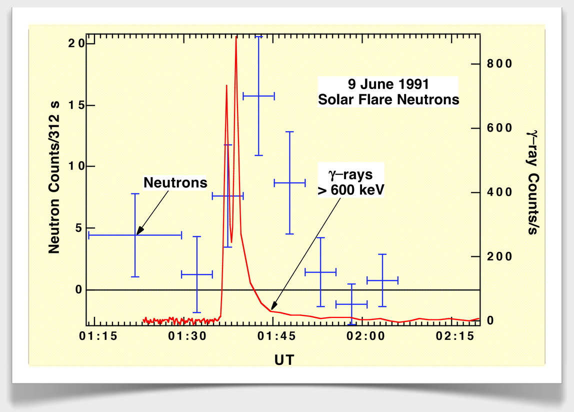
What Neutrons Have Revealed



(Chupp et al., 1987)

1983 June 3

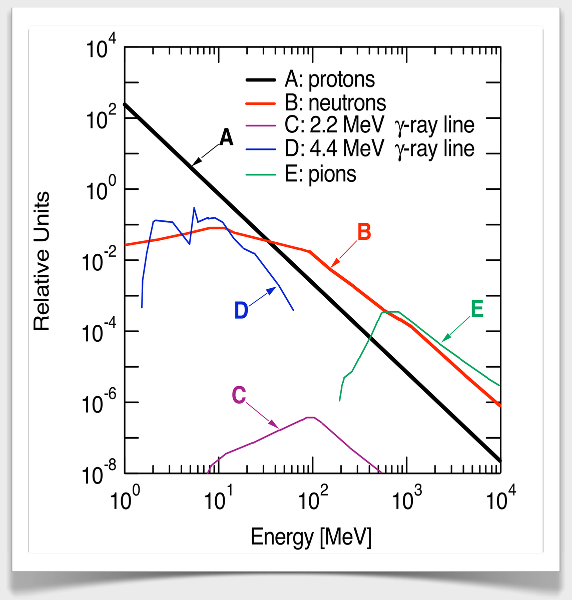
- Solar neutrons detected in the GRS instrument (HE Matrix) and at ground level (Jungfraujoch).
- Because the neutron energies were not measured, the spectrum was inferred by modeling using the pion γ rays as the production profile and the time of detection as a measure of the neutron energy.



(Ryan et al., 1993)

1991 June 9

- In this flare, measured with the COMPTEL instrument, the neutron energies were measured, allowing each neutrons to be properly registered in time with respect to the γ-ray emission. The neutrons above 15 MeV were **emitted later** than the γ rays from protons of lower energy. This is evidence for an evolving proton/ion spectrum.



Neutron vs. γ Cross Sections

The cross sections for producing neutrons spans the entire range from just above 1 MeV to >1 GeV, whereas the γ-ray cross sections (weighted by the input spectrum) concentrate around 10 MeV. **A** is the input proton power-law spectrum, **B** is the resulting neutron spectrum. Others are also shown.

(Debrunner et al., 1997)

Space Based Resources

- PAMELA: Carries a ^{3}He neutron detector (MeV to thermal). However, all but the lowest energy neutrons produce a signal that is not contained in the detector. For example, the range of the recoil particles from the ^{3}He(n, p)T reaction in the gaseous detector is greater than the size of the detector. Also subject to the high neutron background from the Earth and the spacecraft.
- MESSENGER: Neutron/γ instrument (Goldsten et al., 2007) for measuring neutrons <20 MeV. Sensitive to neutrons produced in the spacecraft by galactic cosmic rays or solar energetic particles.

Ground Based Resources

- Neutron Monitors (>500 MeV) An example is Jungfraujoch that registered the
- Muon detectors (>500 MeV)

Gamma Observations

- Measurements or images at 2.2 MeV γrays is a measure of the thermal neutron capture in the lower solar atmosphere (chromosphere, photosphere).

What we do not have

- Solar Orbiter—called for in Mission Concept, none selected in competition
- Solar Probe—called for in Science Definition, but none selected in competition

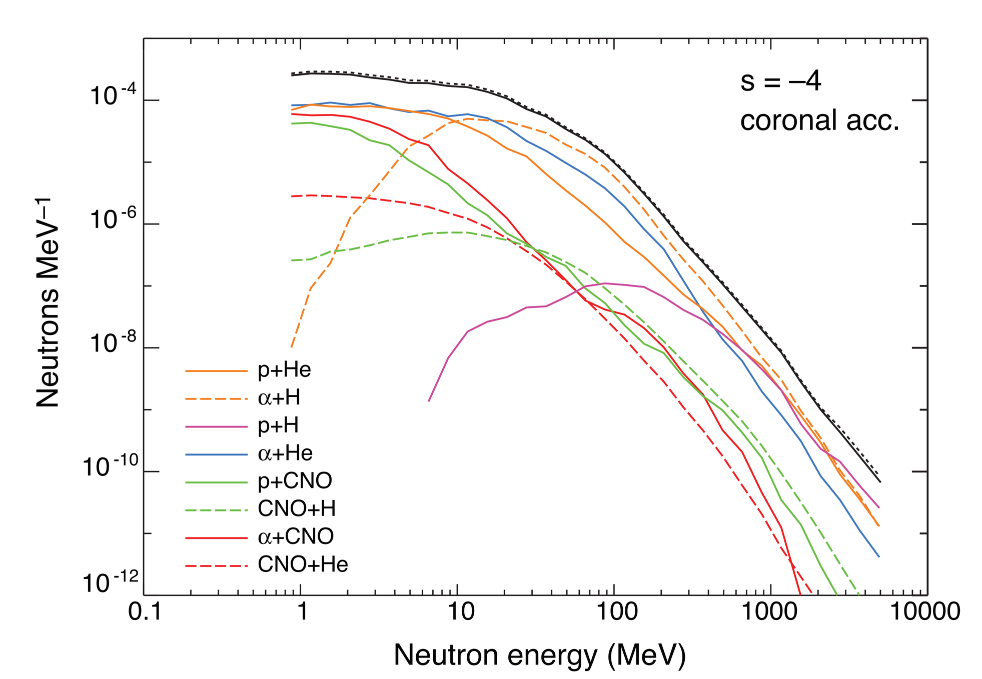
  Both these were intended to measure low energy neutrons in the inner heliosphere, i.e., <10 MeV.

- **There is no spectroscopic measurement performed at any energy by any instrument. (MESSENGER has a very low efficiency spectroscopic mode)**

Today's Science Capability

Low Energy Neutrons

- We first assume that the neutron signal at MESSENGER is well above the cosmic-ray or SEP background. (Avoid well connected events!)
- With no energy measure, the origination time of the neutron as detected with MESSENGER is unknown, other than through modeling.
- The insensitivity of the neutron spectrum below 10 MeV severely limits our knowledge of the neutron spectral shape. See figure below (Share et al., 2011).
- HOWEVER, the intensity of the low-energy neutron emission can be evaluated through the integrated and background-corrected signal.
- This low-energy measure combined with an integrated 2.2 MeV γ-line intensity can provide the total neutron number above and below 10 or 20 MeV.



Predicted neutron spectrum for an E^{-4} power law proton/ion spectrum as measured at MESSENGER distances. The flat spectrum below 10 MeV is a result of the nuclear physics.

High-energy Neutrons

- High-energy neutrons detected at ground level with neutron monitors or muon detectors can be correlated with γ-ray measurements performed with *Fermi* to investigate the high-energy proton/ion population, its spectrum and its evolution.

Why we need real spectroscopy.

With real event-by-event neutron spectroscopy, we can, knowing the neutron velocity, place the its origin in the proper time frame with respect to other flare radiation. We saw for both the 1982 June 3 and the 1991 June 9 flares (and others) that the neutron production need not follow the production of nuclear-line γ rays. Because neutrons are surrogates for different energy protons, measuring their emission curves tells us much about the evolution of the energetic proton/ion spectrum. Is it a slow, progressive process or is it impulsive with an orderly decay or something else? When does it start and when does it finish? With the γ-ray lines sampling such a small section of the proton spectrum, this question is unanswered. At the very highest energies, the pion γ rays (~70 MeV) and the neutrons detected at ground level are well correlated (Lockwood et al., 1997), but what is not known is if there are advanced (as opposed to retarded) neutrons, especially at low energy, indicating the acceleration of lower energy protons in advance of significant γ-ray emission.

Why we need imaging.

Because neutrons are copiously produced everywhere by energetic cosmic rays or galactic or solar origin, background suppression is critical for lowering the sensitivity threshold and allowing for analysis of individual neutrons.

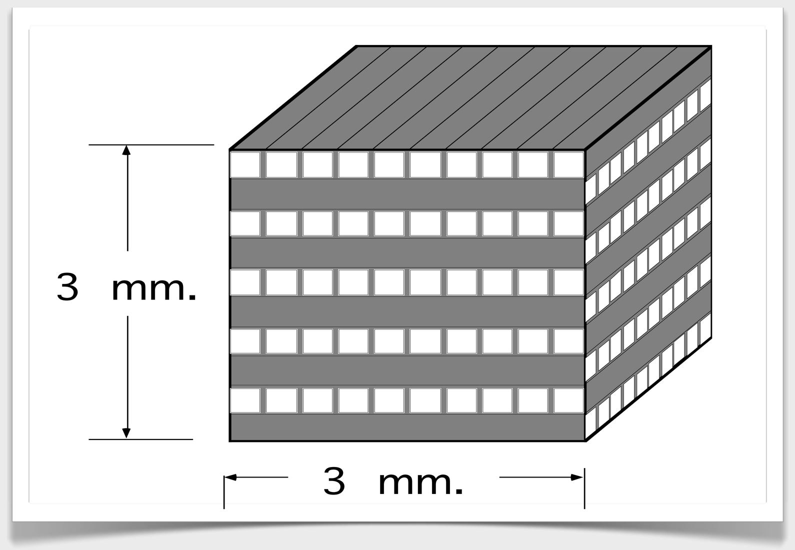
What Can We Do Tomorrow?

Opportunities?

- Major Mission—not likely, given NASA budget constraints from JWST.
- Inner Heliosphere—Solar Probe and Solar Orbiter will not likely carry any dedicated add-on neutron instrument in any form.
- Solar Sentinels—in suspended animation, but would provide 0.3 AU perspective with low-energy neutron sensitivity.
- Explorers—SMEX and MIDEX concepts are viable, either in low-Earth orbit or perhaps smaller versions in high orbits, L1 or solar orbiting. Should be combined scientifically (ideally on same bus)

One possibility

- For a SMEX mission, one needs a compact, low-mass, but still sensitive instrument with the requisite resolution(s).
- Problem is particularly difficult for neutron measurement, because of the intrinsic difficulty of detecting and measuring these particles.
- The SONTRAC concept, conceived by Glenn Frye and Tom Jenkins at CWRU and fleshed out at UNH, is one that allows neutrons to be detected through two scatters in an organic scintillator block. The fine-grained internal structure of the block allows one to image the nuclear reaction (n-p scattering) tracks. This structure is in the form of alternating and mutually orthogonal planes of scintillating fibers. Triggered fibers transmit the scintillation light to 2-d optoelectronic imaging devices affixed to at least two faces of a cube of scintillating fibers.
- By tracking the recoil protons, one can restrict the allowable neutron incident directions to a small solid angle around the Sun.
- A small segment schematic of the SONTRAC instrument is shown below.



A 1/10 schematic of the microstructure of the SONTRAC instrument. Optoelectronic 2-d imaging devices can register the ionization path of a recoil proton.

A double-scatter neutron interaction in a SONTRAC prototype. The ionization tracks shown were produced by recoil protons from neutron collisions. The incident atmospheric cosmic-ray neutron that produced this image was approximately 50 MeV.

Future

- UNH has perfected the technique for fabricating large area scintillating fiber planes.
- A (22-cm) version would have several times the effective area of COMPTEL, the only instrument to spectroscopically measure solar neutrons.
- It would have an equivalent S/N ratio of the COMPTEL measurements.
- Coupled with MESSENGER and ground-based high-energy measurement, our coverage of high-energy solar flares would unprecedented.