Neutron-Decay Protons from Solar Flares as Seed Particles for CME-Shock Acceleration

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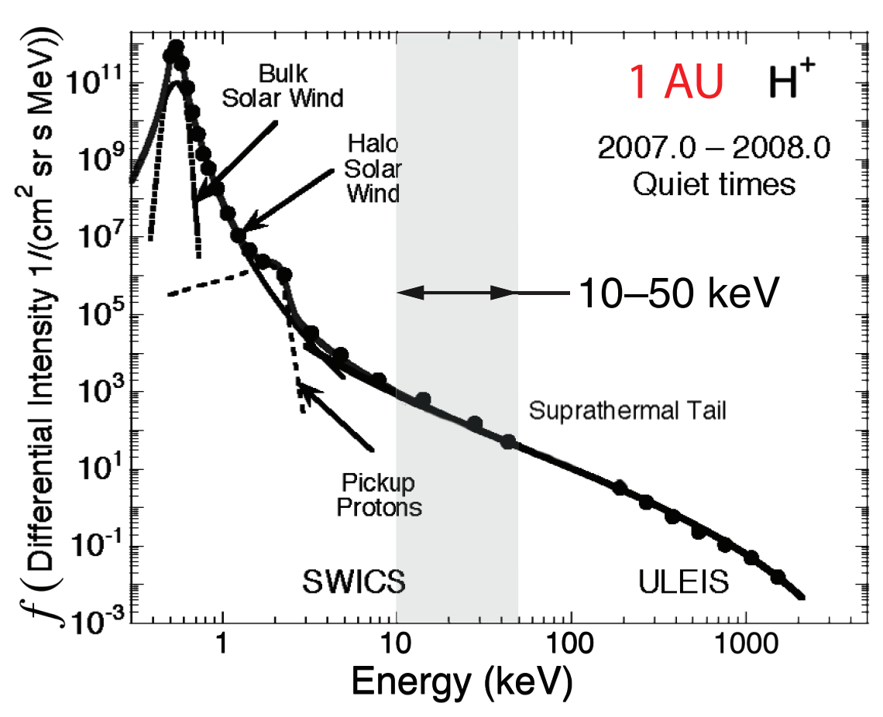
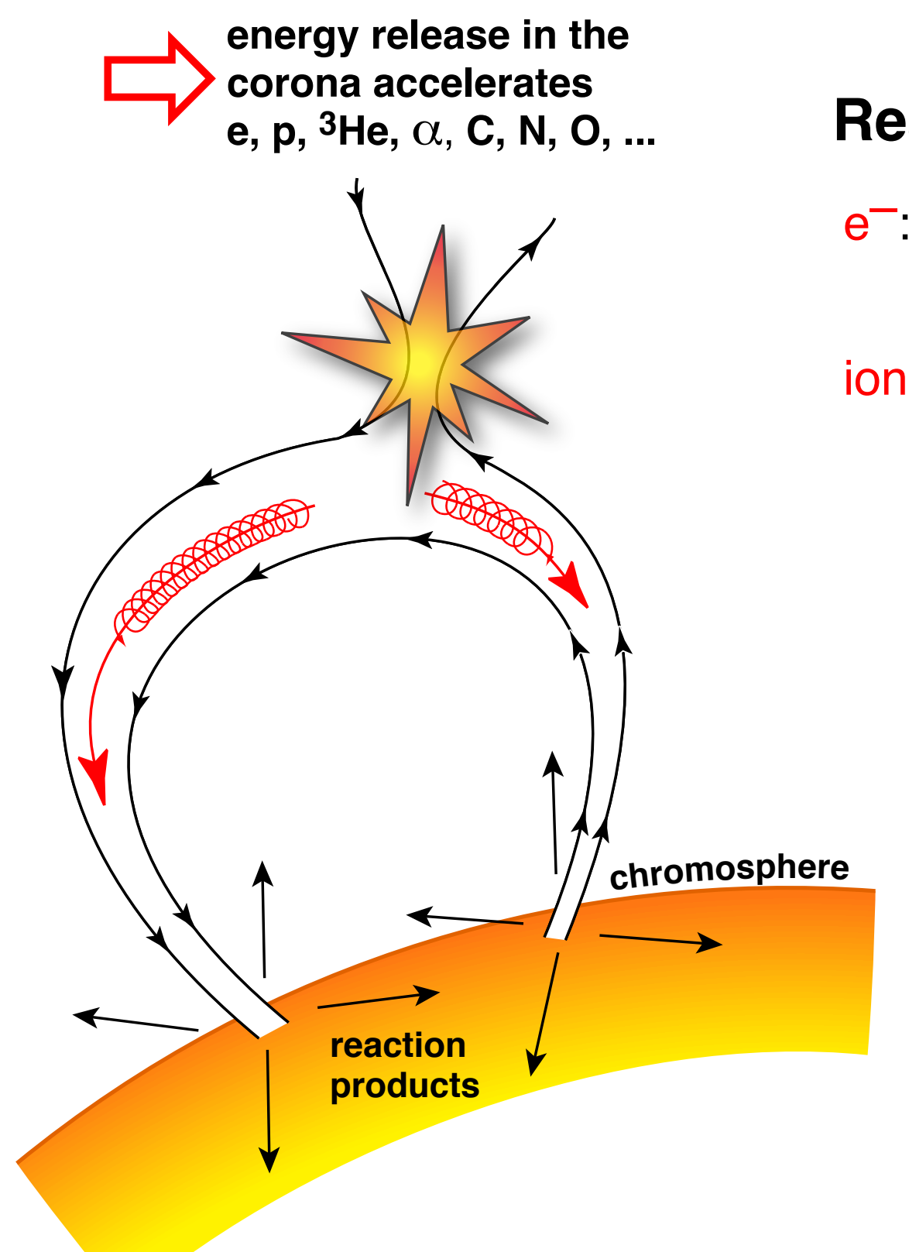
1 Abstract

- Protons in large solar energetic particle events are accelerated in the inner heliosphere by fast shocks produced by coronal mass ejections.
- In the absence of other sources, the protons the shocks act upon would be those of the solar wind (SW).
- Shock-acceleration efficiency depends on the kinetic energy of the protons. For 2000 km s^{-1} shocks, the most effective energies would be 10–50 keV; i.e, within the SW suprathermal tail.
- We investigate a possible additional source of “seed” protons: those from the decay of neutrons produced by solar flares that escape from the Sun into the low corona.
- **Even for optimal flare conditions, the 10–50 keV neutron-decay proton density produced by even a very large solar flare would amount to less than a few percent of that of the 10–50 keV solar-wind suprathermal tail at a few $R_\odot$.**



from Gloeckler *et al.* (2008)

2 High-energy emissions from solar flares include neutrons



Reaction Products of Accelerated Particles

e^-: X- and γ-ray bremsstrahlung

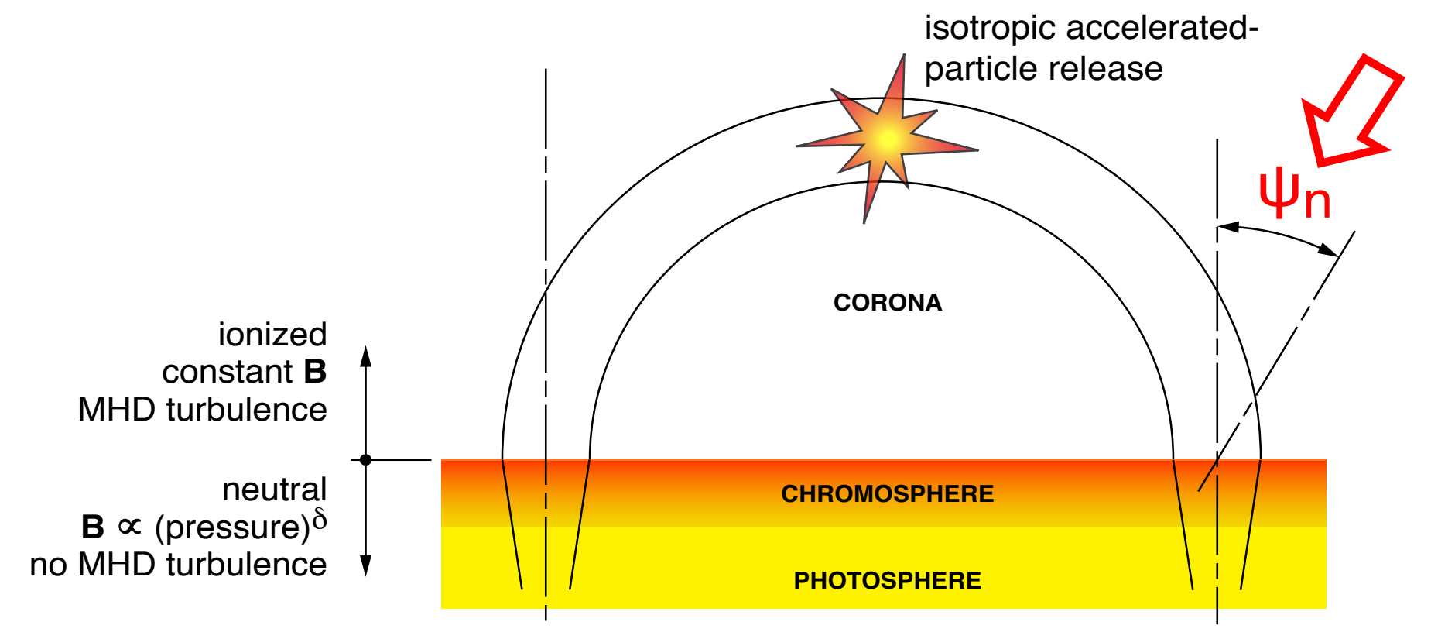
ions: excited nuclei → prompt γ-ray line radiation

radioactive nuclei $\rightarrow \begin{cases}\text{delayed } \gamma\text{-ray line emission}\\ e^+ \rightarrow \gamma_{511}\end{cases}$

$\pi \rightarrow \gamma$ (decay, $e^\pm$ bremsstrahlung, γ_{511})

neutrons $\rightarrow \begin{cases}\text{capture on H} \rightarrow 2.223 \text{ MeV } \gamma\text{-ray line}\\ \text{escape to space}\end{cases}$

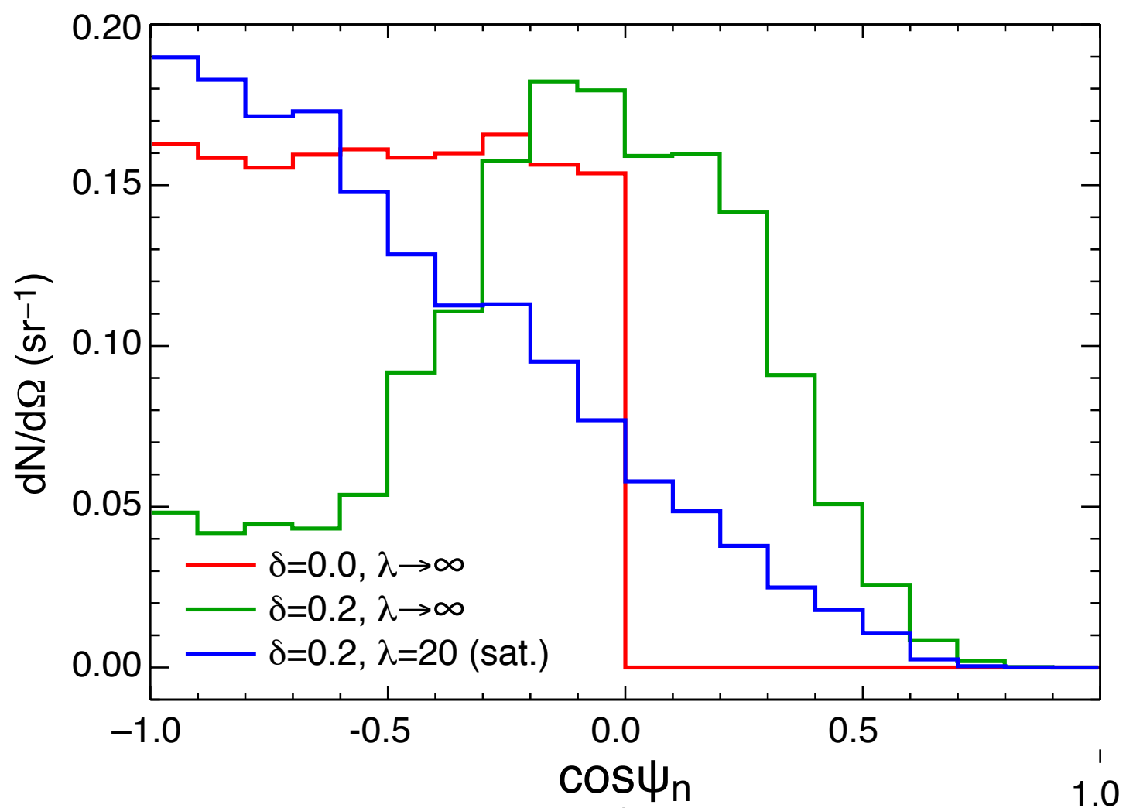
3 Magnetic-loop model used to calculate neutron emission; the important parameters ψ_n, δ and λ



This model has been used to successfully account for the wide range of emissions noted in Panel 2 observed from a large number of solar flares.

- Nuclear interactions of p, ^{3}He and α with all ambient species and their inverse reactions
- Mirroring due to magnetic field convergence: $B(h) \propto P(h)^\delta$
- Scattering due to MHD turbulence replenishes loss cone: $\lambda = \frac{\Lambda}{L_c}$ Λ (mean free path) L_c (loop half length)
- Yields depend on accelerated-particle spectral index, composition
- Yields also depend on ambient composition
- Accelerated-ion number energy spectrum is a power law with index Γ: $dN/dE \propto E^{-\Gamma}$
- ψ_n is the angle between the flare normal and the line-of-sight

4 The interacting-ion angular distribution is not isotropic and depends on δ and λ



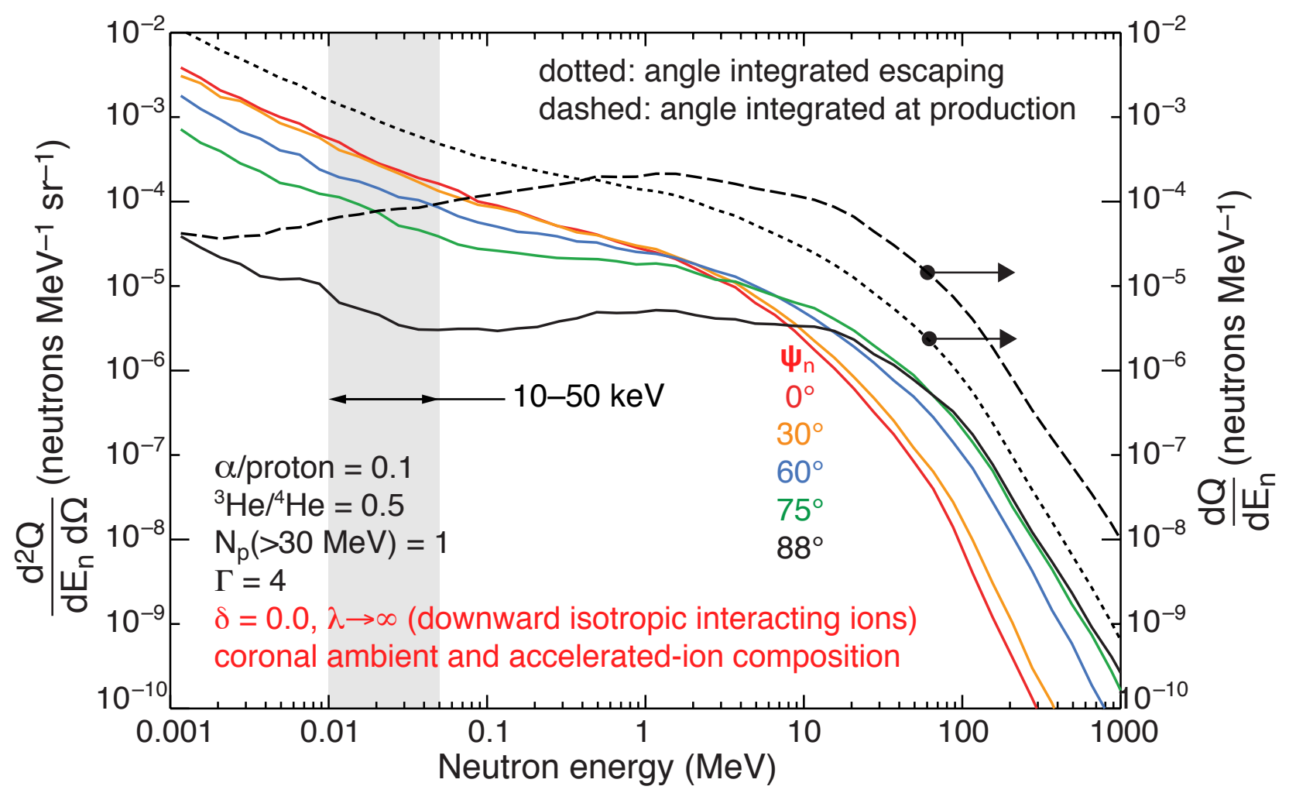
- In the absence of magnetic convergence ($\delta = 0$), there is no mirroring and the interacting-ion angular distribution will be downward isotropic.
- In the presence of magnetic convergence ($\delta \neq 0$), ions mirror, and the interactions occur mostly when they are moving parallel to the solar surface (i.e., a “fan beam” angular distribution).
- Pitch angle scattering causes the loss cone to be continuously repopulated. Therefore, PAS ($\lambda < \infty$) results in more interactions involving downward-directed ions.

5 The escaping-neutron energy spectrum is therefore not isotropic and depends on ψ_n, δ and λ

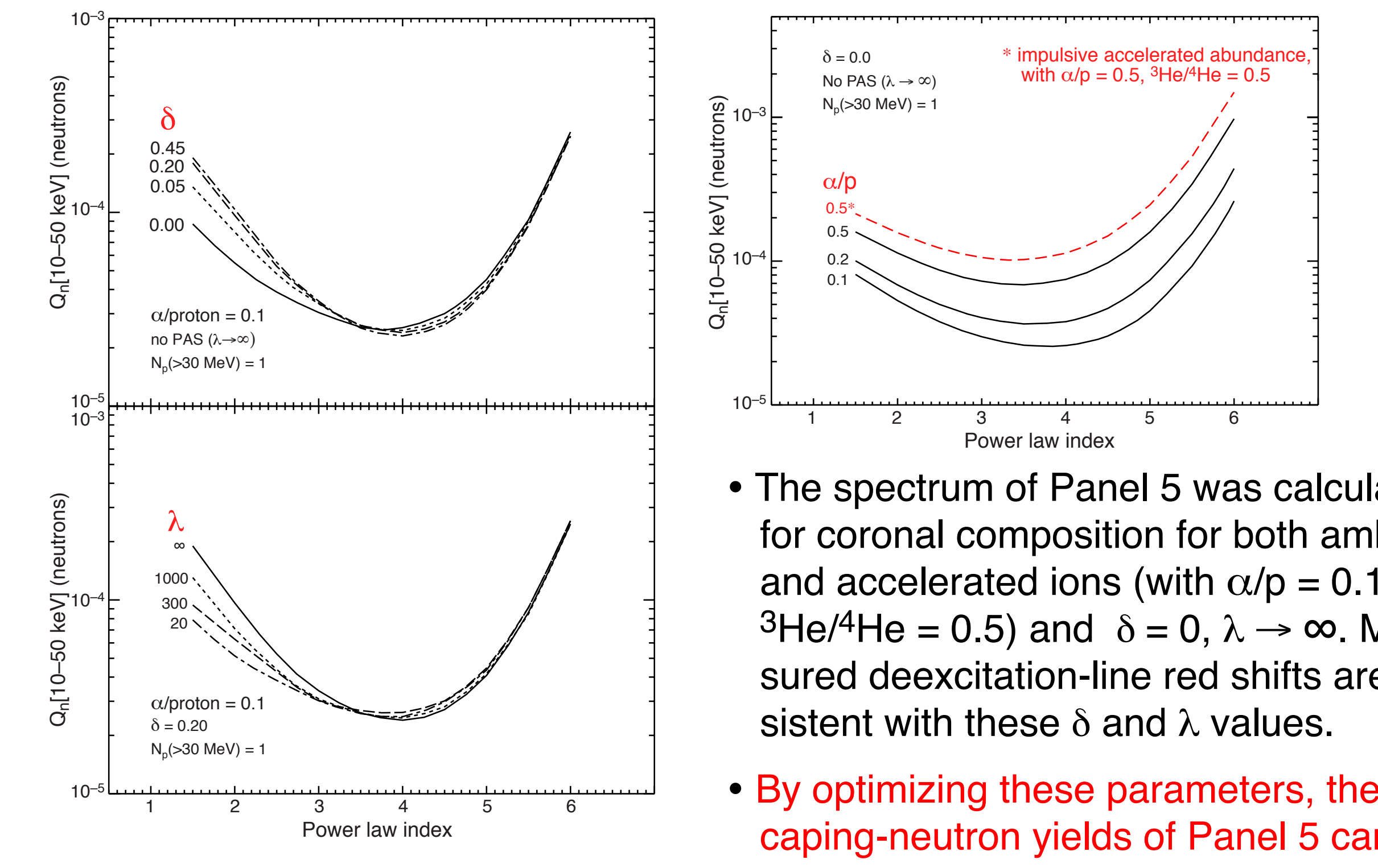
- While low-energy neutrons tend to be produced isotropically, higher-energy neutrons tend to be emitted more in the same direction as the interacting ion.
- Neutrons originally moving upwards will escape without scattering.
- Some of the neutrons originally moving downwards will scatter upwards and escape but with reduced energy.
- Because the interacting ion angular distribution is not isotropic, the neutron angular distribution will also not be isotropic and the spectrum of neutrons escaping from the Sun

$$\frac{d^2Q}{dE_n\,d\Omega}(E_n,\psi_n)$$

will be a function of the angle ψ_n and will depend on the parameters δ and λ.

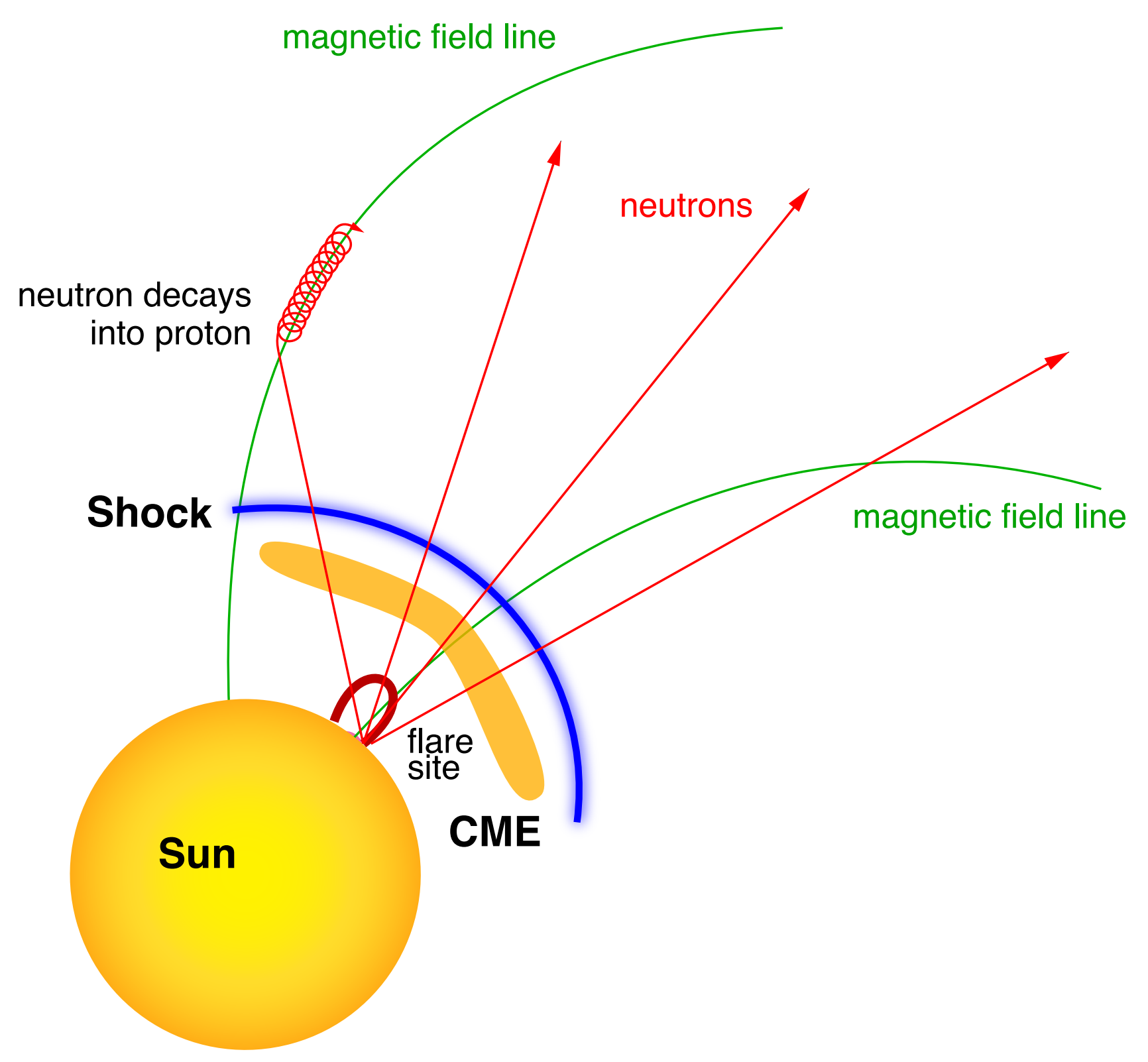


6 Neutron yield dependence (cont.)



- The spectrum of Panel 5 was calculated for coronal composition for both ambient and accelerated ions (with $\alpha/p = 0.1$ and $^3He/^4He = 0.5$) and $\delta = 0$, $\lambda \rightarrow \infty$. Measured deexcitation-line red shifts are consistent with these δ and λ values.
- By optimizing these parameters, the escaping-neutron yields of Panel 5 can be increased, but at most by a factor of ~10.

7 Decay of escaping neutrons produces protons in the inner heliosphere



Free neutrons decay:

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

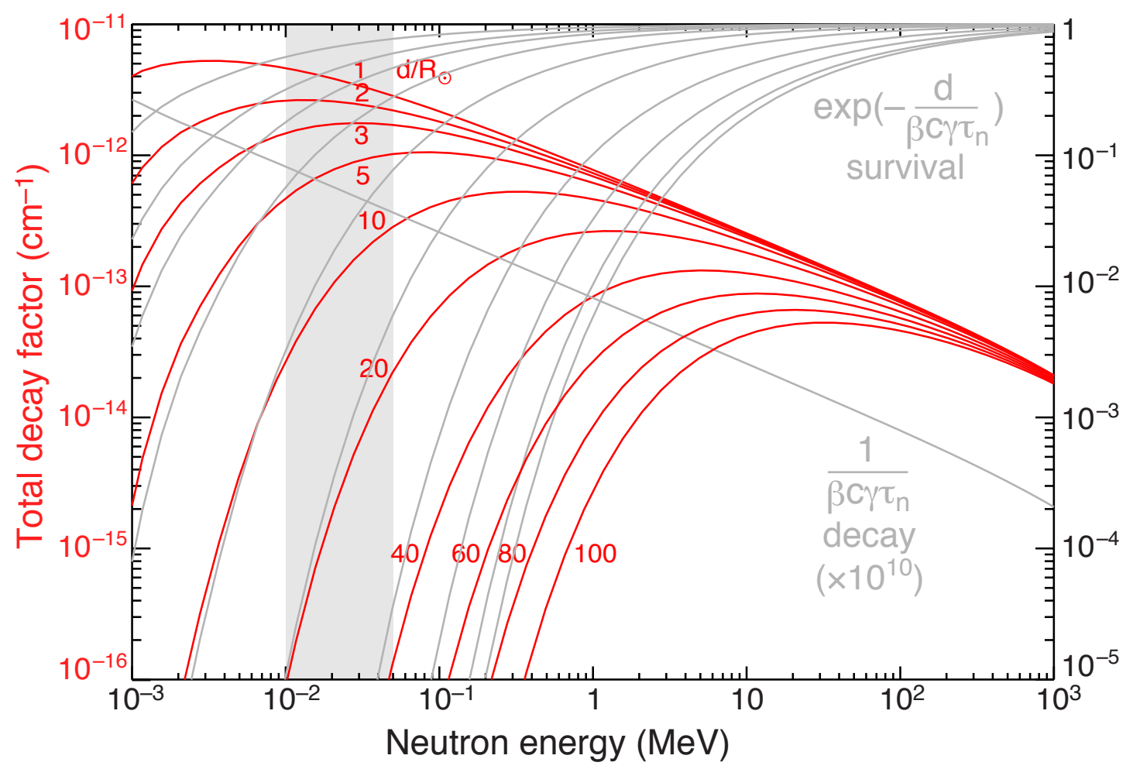
$$\tau_n \cong 882 \text{ s}$$

More lower-energy neutrons are lost to decay due to their longer transit times. <30 MeV neutrons do not survive to Earth and can only be observed with detectors in the inner heliosphere.

8 Neutron-decay proton density along a Parker spiral depends on distance d from the flare and the angle ψ_n

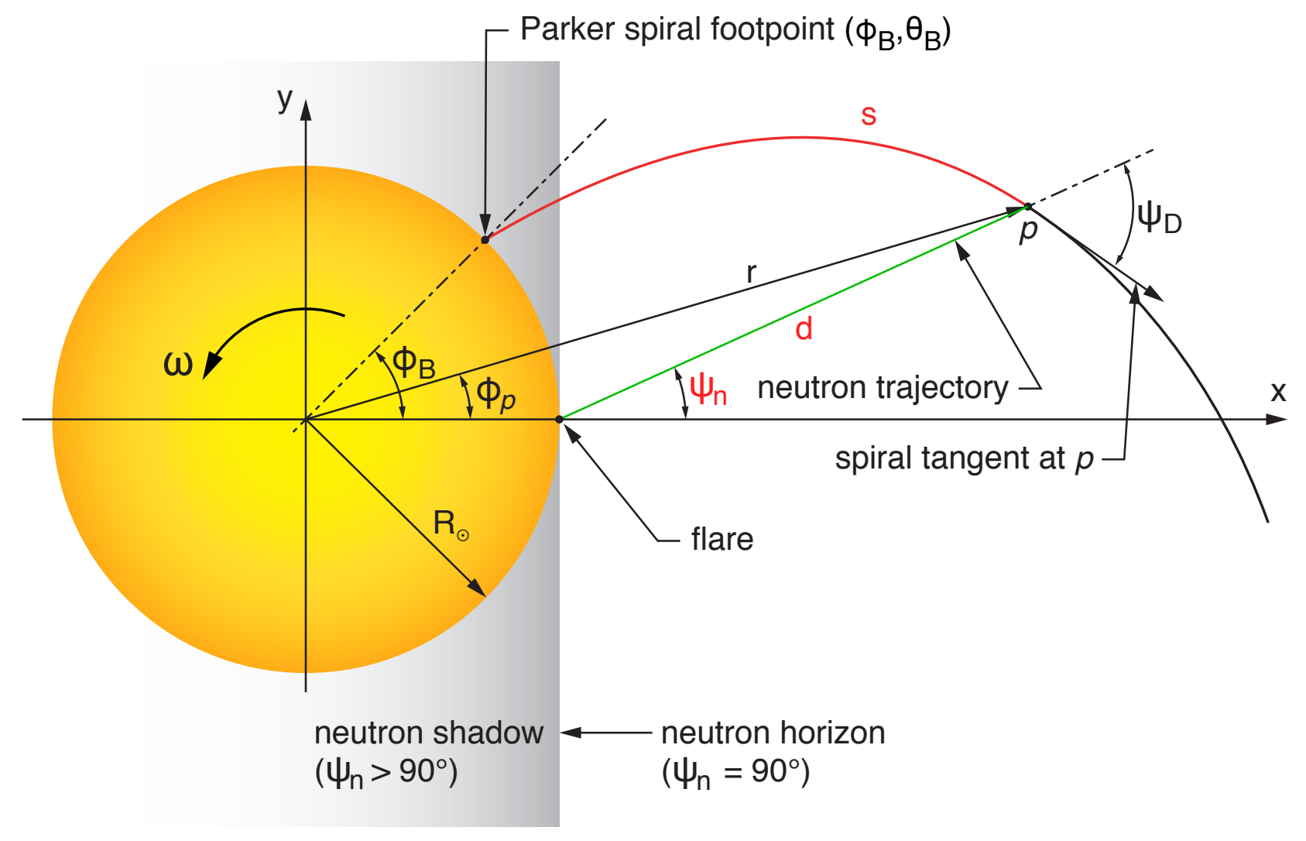
$$n_D(E_n,d,\psi_n) = \underbrace{\left[\frac{d^2Q}{dE_n\,d\Omega}(E_n,\psi_n)\,\frac{1}{d^2}\right]}_{\text{neutron fluence w/o decay}}\ \underbrace{\underbrace{\exp\left(-\frac{d}{\beta c\gamma\tau_n}\right)}_{\text{survival}}\ \underbrace{\frac{1}{\beta c\gamma\tau_n}}_{\text{decay}}}_{\text{total decay factor}}$$

The energy-dependent density of neutrons decaying at a distance d from the flare along an angle ψ_n from the normal at the flare site. This is also the density of the decay protons. The decay proton retains nearly all of the dcaying neutron momentum.



The probablility that a neutron will decay at a given distance d from the flare depends on the neutron energy.

9 Geometrical variables and the Parker spiral

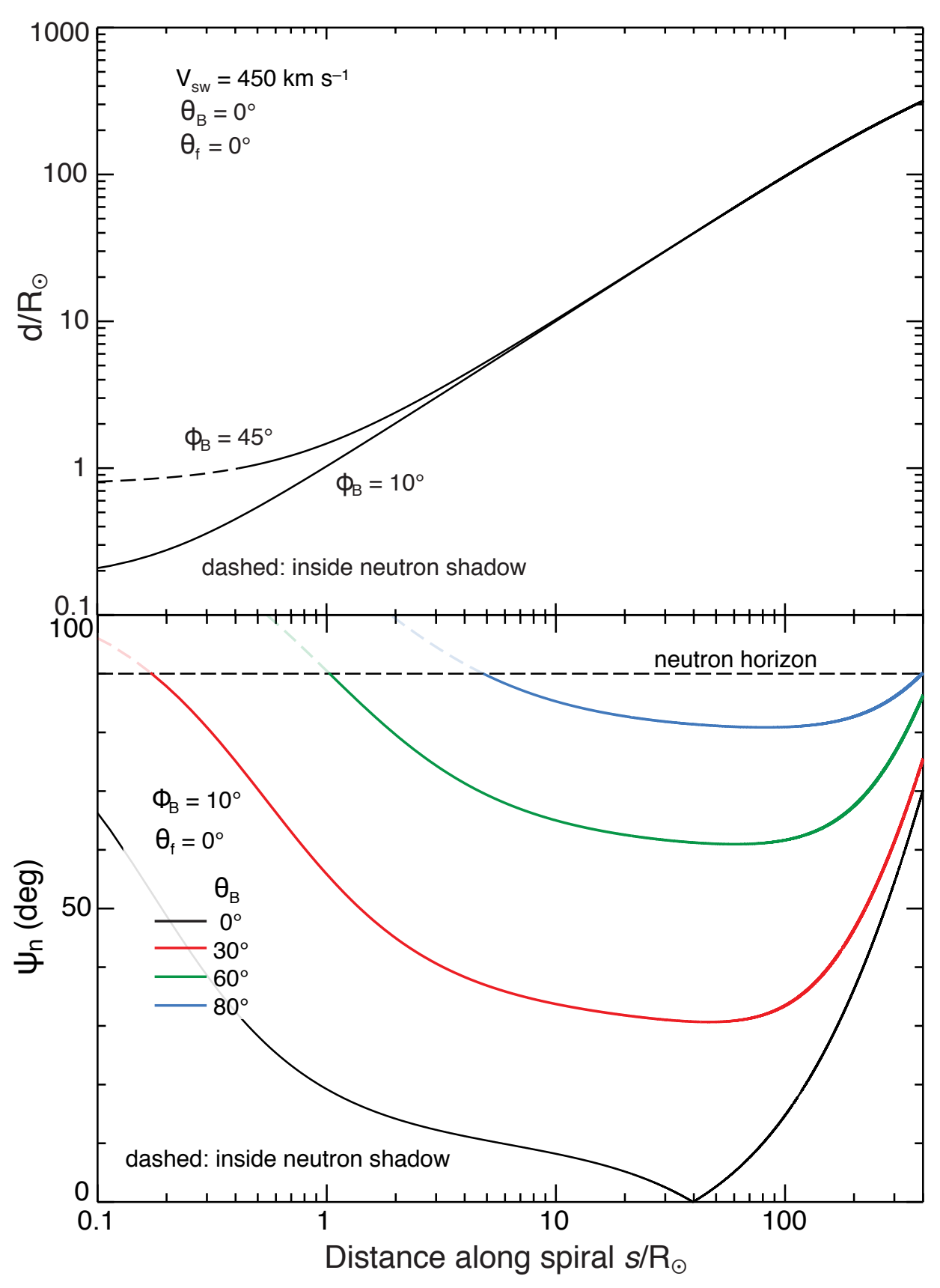


Features on the solar surface are located by traditional longitude and latitude (ϕ,θ). The Parker spiral footpoint is at (ϕ_B,θ_B). The distance along the spiral from the spiral footpoint is s.

Point *p* on the Parker spiral:

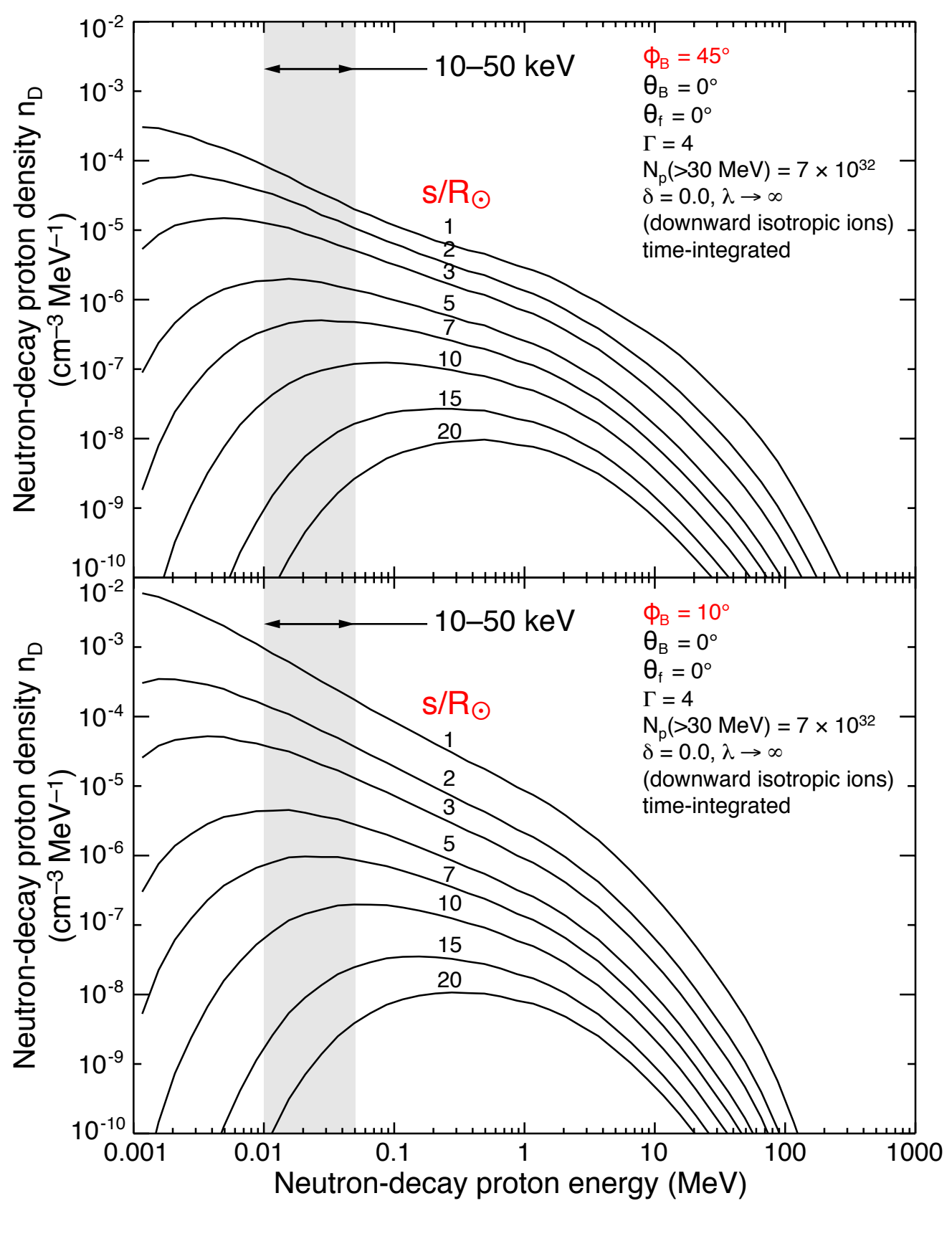
$$r(\phi_p) = R_\odot + \frac{V_{SW}}{\omega}(\phi_B - \phi_p).$$

10 Variation of d and ψ_n with distance along spiral



- Vector calculus provides expressions for d and ψ_n as a function of distance s along the Parker spiral.
- These quantities depend on the location of the spiral footpoint relative to the flare.
- The Parker spiral passes directly over the flare ($\psi_n = 0°$) only when both flare and spiral footpoint have the same latitude.

11 Neutron-decay proton density along the spiral



- Using the expression for n_D (Panel 8), calculated neutron spectra (Panel 5), and the values for d and ψ_n (Panel 10), we calculate the energy-dependent time-integrated density n_D along the spiral for two values of the spiral footpoint location ϕ_B. n_D maximizes at a separation between the flare and the spiral footpoint of ~10°.
- The assumed accelerated-proton spectral index and number are those from the large solar flare of 1991 June 4: $\Gamma = 4$ & $N_p(>30 \text{ MeV}) = 7 \times 10^{32}$.
- Using the measured 1-AU SW differential intensity, f, from Panel 1, the expression $f = v\, n_{SW}/4\pi$, and assuming an r^2 radial dependency, we compare n_{SW} and n_D at $s = 1\ R_\odot$ ($r \cong 2R_\odot$):

E_p (keV)	n_{SW} (cm^{-3} MeV^{-1})	n_D (cm^{-3} MeV^{-1})
10	1	10^{-3}
50	1.9×10^{-2}	1.7×10^{-4}

12 Conclusions and Discussion

- The results of Panel 11 show that the density of 10–50 keV protons from the decay of neutrons produced by even a large solar flare is much less than that of the suprathermal solar wind. Even by optimizing the flare parameters (Panel 6), the neutron-decay proton density from a large flare would amount to only a few percent of that of the SW.
- While neutron-decay protons from one large, typical solar flare cannot produce a significant number of shock seed particles, perhaps a large number of weak events collectively could. The number of energetic events rises rapidly as the event energy decreases. Little is known about neutron production in such weak events, but if it scales with event energy, these small events together may be a significant source of neutron-decay proton seed particles.
- Feldman *et al.* (2015) reported several detections of <10 MeV neutrons from the Sun with *MESSENGER* when it was located in the inner heliosphere. However, the implied number of flare-accelerated protons as calculated with the loop model would be 100 times more than that of the largest flare observed to date, even though the associated flares were minor, casting doubt on their claim of a solar source. If such previously-undetected efficient neutron-producing events are real, their mechanism would have to be different from that of the otherwise-successful loop model. But if they do occur, they may be capable of providing a significant density of neutron-decay protons.

Feldman, W. C., *et al.* 2015, JGR (Space Physics), 120, 8247
Gloeckler, G., *et al.* 2008, in AIP Conference Series, V. 1039, 367–374