Physics of solar neutron production: Questionable detection of neutrons from the 31 December 2007 flare

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[1] Spacecraft observations in the inner heliosphere offer the first opportunity to measure 1–10 MeV solar neutrons. We discuss the cross sections for neutron production in solar flares and calculate the escaping neutron spectra for monoenergetic and power law particle spectra at the Sun and at the distance (0.48 AU) and observation angle of MESSENGER at the time of its reported detection of low-energy solar neutrons associated with the 31 December 2007 solar flare. We detail solar physics concerns about this detection: (1) the inferred number of accelerated protons at the Sun for this modest M2 class flare would have been 10 times larger than any flare observed to date, and (2) the implied energy in accelerated ions would have been 50–10^4 times what we would expect based on the observed energy in nonthermal electrons and the energy in the thermal X-ray plasma. We find that there is no compelling evidence for a high electron/proton ratio in the solar energetic particle (SEP) event, raising concerns that the neutron counts came mostly from SEP ion interactions in the spacecraft; this concern is supported by the similarity of the SEP and neutron count rates. The MESSENGER team made detailed calculations of neutron production from SEP protons. However, if interactions <30 MeV had been included in their calculations and the carbon spacecraft structure were a significant source of secondary neutrons, we estimate that SEP proton and α-particle interactions could account for the observed fast neutron rate. This is due to ^{13}C that has a 3 MeV proton threshold for neutron production and is exothermic for α-particle interactions.

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1. Introduction

[2] *Feldman et al.* [2010] reported the detection at 0.48 AU of 1–8 MeV neutrons from a solar flare on 31 December 2007. The flare was behind the East limb of the Sun for detectors at Earth, but was well observed by the MESSENGER spacecraft on route to Mercury. *Feldman et al.* [2010] did not give the flux of neutrons implied by the reported count rate. The high statistical significance of the rate and its 9 h duration suggests a large number of low-energy neutrons. Instruments at 1 AU cannot directly detect <10 MeV neutrons because their travel time from the Sun (>55 min) is long compared to the lifetime of free neutrons (~15 min exponential lifetime). Only measurements made in the inner heliosphere have the realistic potential of directly detecting these low-energy neutrons. In this paper we discuss the production of low-energy neutrons in solar flares and relate this to the production of higher-energy neutrons and γ rays detected with Earth-orbiting satellites since the late 1970s. A key question in this context is what new information is provided by 1–10 MeV neutron measurements made in the inner heliosphere that cannot be obtained with instruments at 1 AU.

[3] We then evaluate the evidence presented by *Feldman et al.* [2010] and conclude that most, and perhaps all, of the neutron counts detected by MESSENGER were not due to solar neutrons. We detail instrumental, background, and interpretative issues that may have led to the claimed detection.

2. Low-Energy Neutron Production in Solar Flares

[4] Neutrons are produced in solar flares when accelerated ions interact in the chromosphere. There are a variety of

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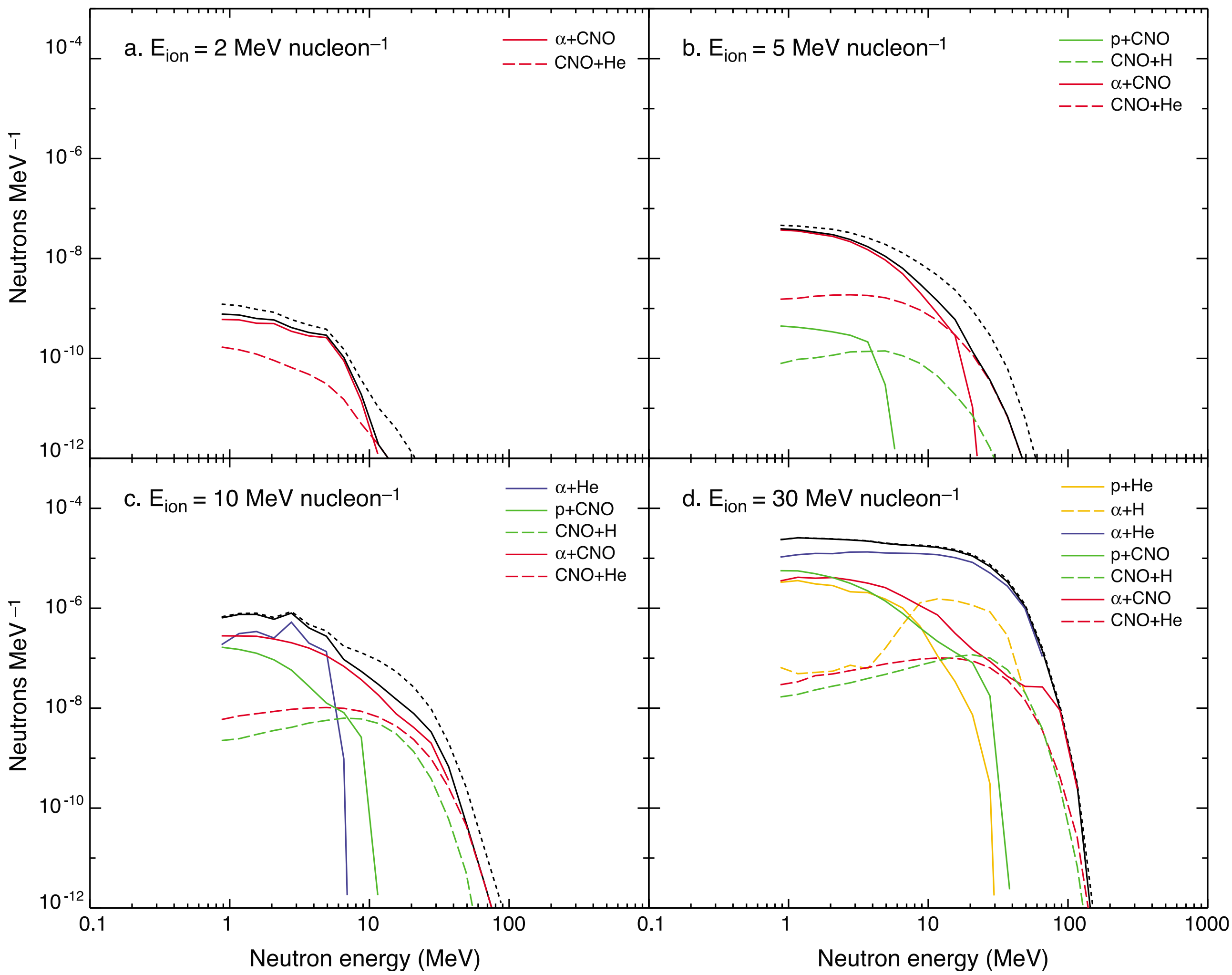

Figure 1. Calculated angle-averaged neutron spectra at the Sun for incident-accelerated particles normalized to one proton and having a coronal composition with α/p = 0.2 (solid black). Spectra from the different production channels are also shown. "CNO" refers to all nuclear species heavier than He. Calculated spectra for accelerated ions with an impulsive SEP composition (dotted black).

interactions that are important for producing neutrons. The most important reactions are proton-on-H, p-on-^{4}He, α-on-H, α-on-^{4}He, p- and α-on-ambient heavy nuclei (direct interactions), and accelerated heavy nuclei-on-H and -^{4}He (inverse interactions) [*Hua et al.*, 2002]. The threshold for neutron production can be <1 MeV nucleon^{-1} for interactions involving α-particles and neutron-rich heavy isotopes.

2.1. Calculated Angle-Averaged Neutron Spectra at the Sun

[5] We performed calculations of neutron spectra assuming that the accelerated particles, have a coronal abundance [*Reames*, 1995], an α/p ratio of 0.2, a downward isotropic angular distribution, and enter a thick target where they interact. We also assumed that the ambient abundance in the thick target is coronal, but with a ^{4}He/H ratio of 0.1.

[6] The neutron spectra were calculated using a modification of algorithms originally developed by *Hua et al.* [2002]. Those original algorithms were optimized for calculating >10 MeV neutron spectra observed at Earth resulting from accelerated particle spectra typically found in solar flares. In that case, the most important neutron-producing reactions are p-on-H, p-on-^{4}He, α-on-H, and α-on-^{4}He at accelerated particle energies greater than a few tens of MeV nucleon^{-1}. Because of the focus in this paper on low-energy neutrons, we have significantly improved the treatment of low-energy interactions involving heavy elements using the nuclear reaction code TALYS. TALYS (http://www.talys.eu/) is a user-friendly, efficient code simulating nuclear reactions of 1 keV to 250 MeV projectiles using state-of-the-art nuclear models and comprehensive libraries of nuclear data covering all main reaction mechanisms encountered in particle-induced nuclear reactions. These algorithm improvements (along with others) will be discussed fully in a separate paper, but some specific improvements will be mentioned in the following discussion.

[7] Figure 1 shows calculated angle-averaged neutron energy spectra at the Sun (in the laboratory frame and before any scattering in the solar atmosphere) for incident accelerated particles, normalized to one proton, at energies of 2, 5, 10, and 30 MeV nucleon^{-1}. In Figure 1a, we show calculated neutron spectra for accelerated particles with initial

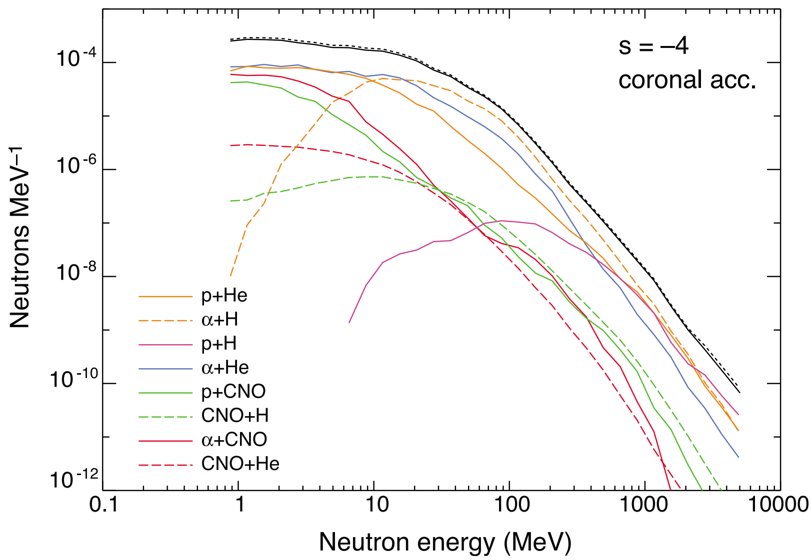

Figure 2. Calculated angle-averaged neutron spectrum at the Sun for accelerated particles following a power law spectrum with index −4 normalized to one incident proton >30 MeV and having a coronal composition with α/p = 0.2 (solid black). Spectra from the different production channels are also shown. "CNO" refers to all nuclear species heavier than He. Calculated spectrum for accelerated ions with an impulsive SEP composition (dotted black).

energies of 2 MeV nucleon^{-1}. At this low energy, the only significant neutron-producing reactions are the exothermic α reactions involving the isotopes ^{13}C, ^{25}Mg and ^{26}Mg (and their inverse interactions) and the low-threshold α reactions involving the isotopes ^{14}N, ^{18}O, ^{22}Ne, ^{29}Si, ^{54}Fe and Fe (and their inverse interactions). We note that the yield from the inverse reactions is reduced relative to that of the direct reactions due to the large Coulomb energy losses of heavy elements in the target. Because of the additional energy available in exothermic reactions, even direct reactions can result in neutron energies greater than 10 MeV. For the inverse reactions, the additional total energy associated with the accelerated heavy particles extends this maximum neutron energy to >18 MeV. At this low accelerated particle energy of 2 MeV nucleon^{-1}, the main modification to the original [*Hua et al.*, 2002] algorithms is a significant increase in the relative contribution of neutron production due to breakup and stripping of the alpha projectile.

[8] At ion energies of 5 MeV nucleon^{-1} (Figure 1b), all of the α-heavy interactions (and their inverse reactions) contribute along with the low-threshold p reactions involving ^{13}C, ^{15}N, ^{18}O and ^{22}Ne (and their inverse interactions). The energies of the neutrons emitted in these reactions extend to >30 MeV. For accelerated ion energies of 10 MeV nucleon^{-1} the α-^{4}He channel becomes available along with more of the p-heavy interactions (and their inverse reactions). The α-^{4}He channel produces ~1–6 MeV neutrons that dominate the low-energy spectrum (Figure 1c); this is the same fusion reaction that produces ^{7}Be which contributes to the ^{7}Li–^{7}Be γ ray line complex [*Kozlovsky and Ramaty*, 1974]. When the accelerated ions reach 30 MeV nucleon^{-1}, neutron production is open to the α-H and p-^{4}He channels and all of the p- and α-heavy reactions (and their inverse interactions). The spectrum is dominated by the α-^{4}He reaction, extends to several tens of MeV, and is relatively flat from 1–20 MeV (Figure 1d). At these accelerated particle energies, the main modifications to the original [*Hua et al.*, 2002] algorithms are (1) particle-energy and target-species dependence of the neutron evaporation temperature and (2) the relative contributions of the evaporation and nonevaporation processes.

[9] We see that even accelerated particles with energies as low as 5 MeV nucleon^{-1} can produce neutrons with energies up to at least ~ 30 MeV, which can be measured at Earth. The presence of ~2–5 MeV nucleon^{-1} ions at the Sun can also be inferred from gamma ray line observations [*Ramaty et al.*, 1979]. Thus measurement of 1–10 MeV neutrons in the inner heliosphere is not a unique source of information on low-energy ions at the Sun. In addition, interactions of accelerated particles of all energies contribute to the flux of 1–10 MeV neutrons in the inner heliosphere.

[10] It is possible that the accelerated particles could have a composition significantly different than coronal material with enhanced helium that we have assumed. For example the γ ray spectrum from the flare on 27 April 1981 was best fit [*Murphy et al.*, 1991] by an accelerated particle composition similar to that of impulsive solar energetic particles [*Reames*, 1995]. The dotted black curves in Figure 1 show the total angle-averaged spectra for this composition. The additional concentration of heavy ions such as Si and Fe increases the numbers of neutrons at high energies, especially for low-energy interacting ions. We note that we have chosen to use a coronal ambient composition that is sometimes required to fit γ ray data rather than a photospheric composition. This choice provides a moderately increased yield of neutrons due to the enhancement of low first ionization potential (FIP) ions, e.g., Mg, Si, and Fe.

[11] Power laws in energy are typically used to represent the accelerated particle spectra in flares. Figure 2 shows the calculated angle-averaged neutron spectrum at the Sun for an accelerated particle spectrum with a differential power law index of −4 normalized to one incident proton >30 MeV.

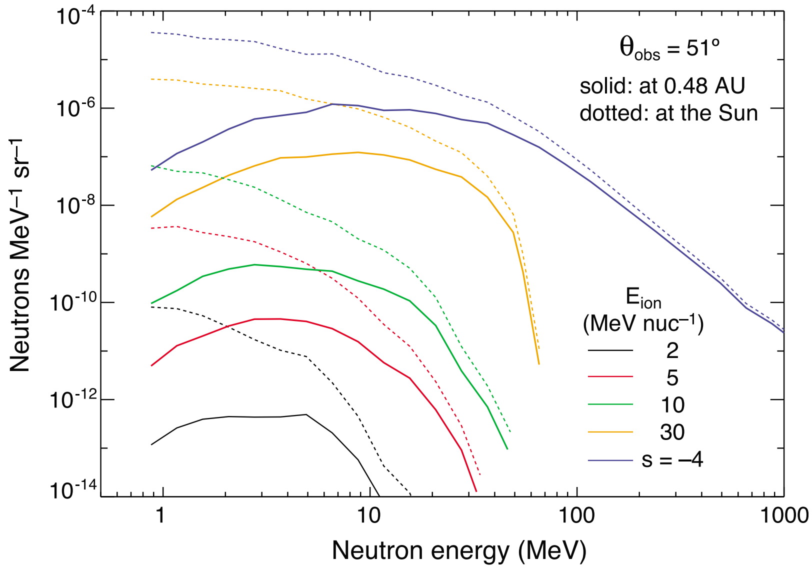

Figure 3. Calculated neutron spectra at 0.48 AU observed at 51° for monoenergetic particles (normalized to one proton at that energy) and for particles with s = −4 power law spectra (normalized to one proton >30 MeV) having a coronal composition with α/p = 0.2 (solid). Calculated spectra at the Sun (dotted).

The solid black curve shows the angle-averaged neutron spectrum for the "coronal" composition used above in the monoenergetic studies presented in Figure 1. We also plot the contributing spectra from the most significant neutron-producing channels. At energies >100 MeV the neutron spectrum is dominated by α-H, α-^{4}He, p-^{4}He, and p-H interactions. We see that the neutron spectrum is flat at energies below 10 MeV. The dotted black curve shows the total neutron spectrum generated by accelerated particles having a composition similar to impulsive solar energetic particles. This spectrum is not significantly different than the spectrum generated by flare-accelerated particles having a coronal composition with enhanced α particles.

2.2. Calculated Neutron Spectra at the Sun and 0.48 AU

[12] The angular distribution of the ions as they enter the thick target affects the spectrum and angular distribution of neutrons that escape from the Sun. The neutron spectra measured in space are significantly different than the angle-averaged spectra shown in Figures 1 and 2, and depend on the viewing angle and distance from the Sun. In Figure 3 we show the calculated neutron spectra at the Sun (dotted) and at 0.48 AU (solid), as viewed from an angle of 51° from the radial direction at the flare site (angle that MESSENGER observed the 31 December 2007 flare). We show the spectra for the four particle energies and for the power law spectrum with index −4 calculated for a downward isotropic distribution of accelerated particles entering the thick target. The spectra of neutrons escaping the Sun at 51° are steeper than the angle-averaged spectra before scattering shown in Figures 1 and 2. The additional low-energy neutrons come from downward-moving neutrons that scatter several times, losing energy and changing their direction. Upward-moving neutrons escape with little scattering.

[13] Due to neutron decay depleting the low-energy part of the escaping spectrum, the 1–10 MeV spectrum observed at 0.48 AU is relatively flat for the monoenergetic and power law particle distributions. The energy peaks of these broad spectra increase moderately with increasing accelerated particle energy. We see that neutrons can reach surprisingly high energies because of the total energy in ions heavier than He.

3. In Situ Detection Versus Remote Detection of Solar Flare Neutrons

[14] The presence of neutrons in solar flares, even neutrons with low energies, can also be detected remotely through observation of a narrow (few eV) 2.223 MeV γ ray line emitted in the formation of ^{2}H in the photosphere by neutron capture on H. These neutrons slow down by elastic collisions and are captured at near-thermal energies. The neutron capture line is the strongest γ ray line produced in flares and its narrow width makes it one of the clearest signatures of ion acceleration and interaction. However, because it is produced in the photosphere, it is heavily attenuated for flares near the solar limb.

[15] An important question is whether remote detection of the 2.223 MeV line with a satellite at Earth is as sensitive to the production of 1–10 MeV neutrons in flares as are *in situ* neutron observations in the inner heliosphere. The answer depends on the relative sensitivities of the γ ray and neutron detectors and on the distance of the neutron detector from the Sun and the longitude of the flare.

[16] At a distance of 0.48 AU the flux of 1–10 MeV neutrons from a flare at a heliocentric angle of 51° produced by α-heavy interactions at 2 MeV nucleon^{-1} is comparable to the flux of 2.223 MeV γ rays at Earth. For an ion spectrum such as a power law with differential index −4 the flux of 1–10 MeV neutrons at 0.48 AU is only about 30% of the line flux at 1 AU. Typical Earth-orbiting γ ray line instruments have effective areas of ~50 cm^2 at 2.223 MeV and

therefore are more sensitive to the presence of low-energy neutrons than ~10 cm^2 neutron detectors at 0.48 AU.

[17] *In situ* neutron detectors at closer distances to the Sun become more sensitive to 1–10 MeV solar neutrons than modest Earth-orbiting γ ray line detectors. For example at $30R_{\odot}$ the 1–10 MeV neutron flux is between 80 and 20 times the neutron capture line flux at Earth for the range of accelerated particle spectra discussed above. However, at these close distances to the Sun it is imperative that the detectors can distinguish between neutrons from the Sun and those produced in the spacecraft by solar energetic protons and heavier ions that arrive close in time with the neutrons.

[18] Although 1–10 MeV neutron observations may not necessarily provide the most sensitive monitor of accelerated ions at the Sun, their observation provides important information on accelerated particle spectra and angular distributions.

4. Conflict Between Reported Neutron Detection and Solar Physics

[19] We use our understanding of neutron production in flares to assess the reported detection with MESSENGER at 0.48 AU of 1–8 MeV neutrons from the solar flare on 31 December 2007 by *Feldman et al.* [2010]. Based on measurements by the X-ray spectrometer on the spacecraft the flare had an equivalent M2 GOES soft X-ray classification [*Krucker et al.*, 2010]. Using the onset of the neutron signal at MESSENGER, *Feldman et al.* [2010] estimated that the maximum solar neutron energy was between 4.8 and 8 MeV under the assumption that the neutrons were produced coincident with the onset times of the X-ray or Type II radio emission, respectively. These two onset times roughly bridge the duration of hard X-rays above the limb of the Sun observed by RHESSI. From the limited scatter of the data points we infer that neutrons were detected with high statistical significance up to 9 h after the flare. Based on our studies of low-energy neutron production we assess whether the MESSENGER neutron spectrometer (NS) did indeed detect neutrons from the solar flare.

4.1. Onset of Neutron Counts

[20] We first consider the rapid onset of 1–8 MeV neutron counts at 01:15 UT which is close to the onset of solar energetic particles at the spacecraft as shown by *Feldman et al.* [2010, Figure 4]. Based on γ ray line observations of numerous flares, accelerated ion spectra on closed loops at the Sun typically can be represented by a power law with differential index of ~−4 [*Share and Murphy*, 2006]. We see in Figure 3 that the neutron spectrum at 0.48 AU for this particle distribution is relatively flat with strong emission up to several tens of MeV. *Feldman et al.* [2010, paragraph 12] state that "…the spacecraft materials are sufficiently massive to soften considerably and attenuate the energy spectrum of neutrons from the Sun." The authors did not quantify this effect on a solar neutron spectrum, such as shown in Figure 3, passing through the spacecraft. Not having this information we estimated the possible extent of this softening using a GEANT4 calculation and assuming that solar neutrons first have to pass through 20 g cm^{-2} of carbon. We found that about 50% of the detected 1–8 MeV neutrons would actually have come from solar neutrons of higher energies. These higher-energy neutrons would have arrived earlier than solar 4.8–8 MeV neutrons, producing a gradual increase in count rate before 01:15 UT and not the rapid increase that MESSENGER observed. This is an important effect and needs to be calculated more accurately with the actual spacecraft mass model. Such a calculation is beyond our capabilities and the scope of this paper.

[21] The only way to produce the observed rapid onset is to limit the solar neutron energies to below 10 MeV. From Figure 3 we see that this can occur if the accelerated ions at the Sun only reached energies of ~2 MeV $nucleon^{-1}$. This would require a high flux of low-energy ions at the Sun as we discuss below in section 4.2. If scattering of low-energy neutrons in the spacecraft before they reach the NS is taken into account, we estimate that the implied flux of flare-accelerated ions would be even higher.

4.2. Implied Number of Accelerated Ions at the Sun

[22] As we noted earlier, the high count rate of fast neutrons at MESSENGER suggests a high flux of solar neutrons. *Feldman et al.* [2010] did not estimate the flux of solar neutrons that the counting rate implies. On the basis of the time profile shown by *Feldman et al.* [2010, Figure 5], we estimate that ~2×10^4 1–8 MeV fast neutrons would have been counted by MESSENGER from 01:15 to 09:00 UT, if we include the extended safe mode period by interpolation. There is no mention of the effective area of the neutron detector in the paper. But if we assume that the efficiency of the 100 cm^2 plastic detector for neutrons incident on the NS is about 10% then the effective area for 1–8 MeV neutrons would be 10 cm^2. As solar neutrons would have to pass through a significant amount of spacecraft material before reaching the NS, 10 cm^2 is probably an upper limit. Thus we estimate that MESSENGER observed a total fluence of $>2 \times 10^3$ neutrons cm^{-2}.

[23] We can estimate the number protons at the Sun required to produce this neutron fluence. We performed the calculations assuming a power law spectrum of accelerated ions with index −4 for two angular distributions: downward isotropic and fan beam (particles mirroring parallel to the solar atmosphere). For the neutron fluence of 2×10^3 neutrons cm^{-2} we estimate that a total of $(0.8 - 1.3) \times 10^{34}$ protons with energies >30 MeV had to be accelerated in the 31 December 2007 flare. For a harder spectrum with index −2.5 the number would be reduced about 40%. If the neutrons had been produced by monoenergetic 5 MeV $nucleon^{-1}$ ions, $>10^{38}$ protons at the Sun would have been required. If the neutrons had been produced by monoenergetic 2 MeV $nucleon^{-1}$ ions, 4×10^{40} protons at the Sun would have been required. These numbers of protons are at least an order of magnitude higher than inferred from the GOES X12 + 4 June 1991 flare, one of the largest γ ray line flares observed to date [*Murphy et al.*, 1997].

4.3. Comparison With Neutron Capture Line Fluxes in Flares and Quiescent Periods

[24] In a typical γ ray line flare such a large number of protons would have also produced an intense flux of nuclear de-excitation lines and the prominent neutron capture line. We estimate the strength of the accompanying 2.223 MeV neutron capture γ ray line based on this large number of protons. For the same power law spectrum with index −4

and angular distributions we estimate that a detector at Earth would have observed a 2.223 MeV line fluence of $6 \times 10^3 \gamma$ cm^{-2}. This is about a factor of 5 larger than observed in any γ ray flare observed to date. Observation of such a high flux would have confirmed the MESSENGER neutron detection. Because there were no γ ray measurements made during the 31 December 2007 flare, we cannot explicitly rule out the possibility that this was simply the largest high-energy flare ever observed.

[25] However, a typical M2 soft X-ray flare is not such a prolific source of 2.223 MeV line emission. In observing 300 flares the γ ray spectrometer on the Solar Maximum Mission (SMM) satellite barely observed the neutron capture line from flares with X-ray classifications of M5 or lower, with 2.223 MeV fluences of only ~1–2 γ cm^{-2} [*Vestrand et al.*, 1999], 0.1% of that implied by the *Feldman et al.* [2010] measurement.

[26] Perhaps the flare was not typical in that it only produced neutrons and not nuclear line and continuum emission above ~300 keV (e.g., the ion spectrum extended only to energies of a few MeV nucleon^{-1}, below the threshold energy for most nuclear line production, and there were no electrons above ~500 keV). However, any interactions producing neutrons would also necessarily produce the neutron capture line, unless the neutrons were produced well above the chromosphere so that they could not efficiently be captured on H. Had the neutrons been produced by a monoenergetic 5 MeV nucleon^{-1} flux of accelerated ions, the neutron capture line flux at Earth would still have been $2.5 \times 10^3 \gamma$ cm^{-2}.

[27] One way to test the plausibility for such an atypical flare is to search for 2.223 MeV line emission outside of times when γ ray (emission >300 keV) flares have been observed. A conservative limit on the flux in this line during periods with no γ ray flares is $\sim 7 \times 10^{-5} \gamma$ cm^{-2} s^{-1} based on a study with the SMM spectrometer [*Harris et al.*, 1992]. For the approximate 4 year observing period during which this limit was obtained the total fluence of 2.223 MeV photons was <9000 γ cm^{-2}, at most only 3 times higher than the neutron capture line fluence that would have been observed at Earth from the 31 December flare alone based on our estimates above.

4.4. Energy Constraints

[28] Another constraint on the large fluence of solar neutrons implied by MESSENGER observation can be set when one considers energetics. The energy in accelerated ions required to produce the neutrons ranges from $\sim 5 \times 10^{31}$ erg for a very hard spectrum (power law with index −2.5) to $\sim 10^{34}$ erg for more typical spectra observed in flares (power law with index −4); the energy in monoenergetic 5 MeV nucleon^{-1} ions would be $\sim 2 \times 10^{33}$ erg; the energy in monoenergetic 2 MeVnucleon^{-1} ions would be $\sim 2 \times 10^{35}$ erg. This large amount of energy must be dissipated in the solar atmosphere and be emitted as thermal energy.

[29] *Emslie et al.* [2004] found that the energy in both nonthermal electrons and ions in the 21 April and 23 July 2002 X class flares, $\sim 10^{31}$ erg, was comparable to the peak thermal energy in the >10 MK thermal X-ray emitting plasma measured by GOES and RHESSI. *Krucker et al.* [2010] used RHESSI, MESSENGER, and GOES observations to estimate that the nonthermal electron energy in the 31 December 2007 M2 class flare was $>10^{29}$ erg (assuming a 16 keV threshold energy) and the peak thermal energy was $\sim 6 \times 10^{29}$ erg. From this and the *Emslie et al.* [2004] study we would expect that the energy in accelerated ions would not have been much higher than $\sim 10^{30}$ erg. This energy is about a factor of 50 to 10^4 lower than the energy in ions estimated for the December 2007 flare based on the reported neutron observations.

[30] *Krucker et al.* [2010] used GOES, MESSENGER, and RHESSI thermal X-ray measurements to conclude that by 30 minutes after the onset of the flare most of the thermal emission was detected by GOES. This thermal emission decreased rapidly after the peak of the flare, dropping by a factor of at least 20 after 3 h. This decrease is comparable to what was observed in the 21 April and 23 July 2002 flares discussed above. In contrast, the neutron counting rate reported by *Feldman et al.* [2010] 3 h after the onset of the flare had not changed significantly. It is hard to understand how the energy deposited by the ions producing these neutrons would not have been detectable in the GOES soft X-ray emission at these later times.

[31] In summary we find significant solar physics issues if the neutrons observed by MESSENGER originated from the site of the 31 December 2007 flare.

5. Possible Explanation for the MESSENGER "Solar Neutron" Observations

[32] Our solar physics arguments above suggest that a solar flare origin for most of the neutrons observed by MESSENGER is implausible. Below we argue that the accompanying solar energetic particle (SEP) event offers a better explanation for counts classified as neutrons in the MESSENGER NS. Because the flare was behind the East limb of the Sun as viewed from Earth there was no magnetic connection to Earth and therefore no measurements of SEPs by spacecraft other than those made by MESSENGER. We first briefly describe how the accompanying SEP event was detected and its characteristics.

5.1. MESSENGER SEP Capability and Observations

[33] The MESSENGER Energetic Particle Spectrometer (EPS) [*Andrews et al.*, 2007] was designed to detect electrons from 0.025–1.0 MeV and protons from 0.025–3.0 MeV. Distinguishing energetic electrons and ions in the EPS relies on a time-of-flight (TOF) system that failed prior to the December event. With the failure of the TOF, the only quantity measured by the EPS for each particle is the energy deposited in a single 500 μm thick solid state detector (SSD), which could be significantly less than the total energy of the particle. This single measurement is also inadequate for particle identification. As a result, the "electron" time lines displayed by *Feldman et al.* [2010, Figure 5a] can contain a mixture of electrons and ions. Moreover, there is also no anticoincidence element to veto high-energy particles that exit through the sides or the back end of the instrument. The EPS is therefore also sensitive to electrons with energies >1 MeV and protons with energies >3 MeV. As discussed below, this sensitivity to high-energy particles affects the arguments of *Feldman et al.* [2010] that the EPS was primarily responding to low-energy electrons.

[34] Elements of the neutron spectrometer (NS) can also be used as solar energetic particle detectors [*Feldman et al.*, 2010]. The lithium glass (LG) thermal neutron detectors are sensitive to electrons from 0.3 to 2 MeV and to protons <30 MeV. Double coincidences between a single LG and the borated plastic (BP) fast neutron detector provide the capability for detecting 2 to 20 MeV electrons and 30 to 120 MeV protons. Triple coincidences between the BP detector and two LG detectors on either side provide sensitivity to electrons >20 MeV and protons >120 MeV.

[35] Assuming the double and triple coincidence rates are due to energetic protons and not electrons, we can estimate the proton spectrum just before the safe hold based on their ratio. After the safe hold the triple coincidence rate was consistent with zero and such an estimate was not possible. Using the geometric factors given in the paper we infer that the flux of 30–120 MeV protons was about 4.6 cm^{-2} s^{-1} sr^{-1} and of >120 MeV protons was about 1.1 cm^{-2} s^{-1} sr^{-1}. Assuming a power law spectrum, the ratio of these two fluxes implies a differential index of about −2.2. If the SEPs had a high concentration of ions such a hard spectrum has implications for neutron production in the spacecraft which we discuss in section 5.2 [*Feldman et al.*, 2010], however, argue that the SEPs were dominated by electrons. We address the evidence for this below.

5.1.1. SEP Electron/Proton Composition

[36] *Feldman et al.* [2010] argued that particles detected after the onset of the SEP event until safe hold had to be electrons because protons with energies below ~1 MeV could not arrive by that time. However as discussed above the EPS is sensitive to protons well above its 3 MeV upper energy cutoff, which could have arrived by that time. There was no sign of velocity dispersion in the EPS energy channels consistent with detection of only <1 MeV solar electrons [*Feldman et al.*, 2010]. However, this lack of detectable dispersion could also have been due to protons with energies well above the nominal passbands for registering in the EPS, as discussed above. In fact the presence of >120 MeV protons and/or >20 MeV electrons is implied by the simultaneous onsets of the EPS and the triple coincidence rates in the NS.

[37] *Feldman et al.* [2010] also appeal to an indirect argument to reject the presence of high-energy protons. Specifically, they argue that if there were such high-energy protons, there would have been lower-energy protons, below 1 MeV. They state that the later arrival of these low-energy protons would have distorted the EPS 0.6–1 MeV time lines in ways that are not observed, suggesting that the ion flux was completely overshadowed by the electron flux. This conclusion does not take into account the sensitivity of the EPS 0.6–1 MeV channel to much higher energy particles. Therefore, without quantitative modeling that takes this sensitivity into account, their argument is not compelling.

[38] *Feldman et al.* [2010] also argue, based on coincidence of the SEP onset and MESSENGER crossing of a tangential discontinuity that the energetic particles originated from a spatially confined impulsive event or several such events and not from an extended interplanetary shock. The tangential discontinuity can explain the observed lack of velocity dispersion among the onsets of charged particle channels in the EPS and NS. But if the detected neutrons really are of solar origin, it is an unexplained coincidence that the count rate for these neutrons, whose transit from the Sun is unconstrained by magnetic fields, should also have their onset at the same time. Moreover, if the SEPs observed by MESSENGER were from the same source that produced solar neutrons, it is difficult to understand why electrons could escape while so few of the ~10^{34} protons needed to explain the solar neutron observations could not.

[39] We conclude that there is no compelling evidence that the composition of the SEP event was dominated by electrons. Indeed, *Moses et al.* [1989] performed a systematic survey of interplanetary electron events with fluxes >10 MeV that were associated with solar flares from 1978–1982. They found that the minimum p/e flux ratio at 15 MeV was ~0.5, with the ratios for most of the other events orders of magnitude larger. If the SEP event can contain a significant fraction of ions the *Feldman et al.* [2010] study of secondary neutron production becomes even more important.

5.2. SEP Origin for the MESSENGER Fast Neutron Counts

[40] A troubling characteristic of the time profile of the fast neutron count rate is that it was remarkably similar to that of the SEP rate during both onset and decay phases of the event [see *Feldman et al.*, 2010, Figures 4 and 5]. The onset times of the neutron and particle events were consistent to within a few minutes and, as the authors pointed out, there are "similarities of their decay phases." This raises concerns that the counts ascribed to solar neutrons may in fact be due to secondary neutrons from interactions of SEP ions with spacecraft material.

[41] The NS cannot distinguish between primary solar and secondary spacecraft neutrons. *Feldman et al.* [2010] qualified their claims for a solar origin of the neutrons with concerns that some of them may have been produced by SEP proton interactions in the spacecraft. They used a detailed spacecraft mass model and MCNPX code [*Pelowitz*, 2008] and geometric factors based on a complex analysis of galactic cosmic rays and the SEP event. Assuming all of the SEP particle were protons *Feldman et al.* [2010] concluded that the number of secondary neutrons from SEP interactions after the safe hold was at most 20% of the total number of fast neutron counts.

[42] *Feldman et al.* [2010] calculated secondary neutron rates at the NS detector as a function of proton energy. The results are plotted by *Feldman et al.* [2010, Figure 8] for proton energies >30 MeV. They assumed that all the particles detected by the double coincidence between the LG and BP were protons and the SEPs had a spectrum that followed a power law with differential index of −3.5. This −3.5 index was determined from measurements of the 20 February 2002 SEP event observed at 1 AU discussed by *Feldman et al.* [2010].

[43] We are concerned that the secondary neutron yield calculated by *Feldman et al.* [2010] may have only been determined for proton energies >30 MeV [see *Feldman et al.*, 2010, Figures 8 and 9]. *Feldman et al.* [2010] state that 30 MeV is "the threshold energy for the generation of secondary neutrons through interactions with spacecraft material". *Lawrence et al.* [2010] discuss the important spacecraft materials that affect neutron transport; these include the carbon composite structure, nitrogen, oxygen, and hydrogen in the fuel, and heavier materials in elec-

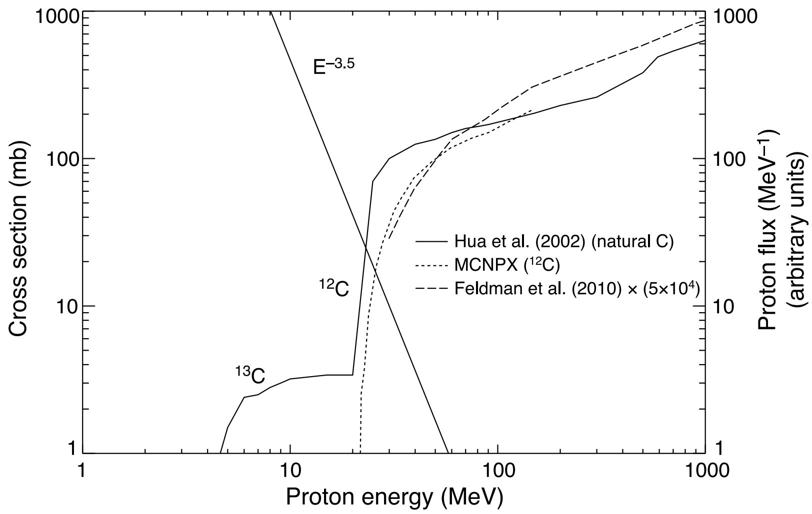

Figure 4. Total neutron production cross section versus energy for proton interactions on natural carbon [from *Hua et al.*, 2002] (solid). Total cross section for neutron production p-on-^{12}C used in MCNPX (dotted). Rates (arbitrarily normalized) of fast neutrons at the NS calculated by *Feldman et al.* [2010, Figure 8] using MCNPX [*Pelowitz*, 2008] for protons >30 MeV interacting in the MESSENGER spacecraft. We also plot a differential power law spectrum that reveals the importance of particle interactions below 30 MeV.

tronics and wiring. The carbon structure is in close proximity to the NS and had the largest affect on the modeled transport. Natural carbon is made up of ~99% ^{12}C and ~1% ^{13}C with neutron production thresholds 19.6 and 3.2 MeV, respectively, for proton interactions. (The production thresholds on ^{14}N and ^{16}O are 6.3 and 17.2 MeV, respectively.) We have studied how the lower carbon threshold energies might have affected the estimated yield of secondary neutrons at the NS.

[44] We plot the total cross section for neutron production by protons on natural carbon [*Hua et al.*, 2002] in Figure 4, showing both the ^{12}C and ^{13}C contributions. The total neutron production cross section calculated using TALYS (see section 2.1) is in excellent agreement. For comparison we also plot the total neutron production cross section on ^{12}C as given in the MCNPX code; it has a somewhat higher threshold and rises more slowly than that given by *Hua et al.* [2002]. The 0.5–7.5 MeV neutron counting rate, as a function of energy, from isotropic proton interactions given by *Feldman et al.* [2010, Figure 8] is also plotted in Figure 4. Its shape is similar to that of the MCNPX total neutron cross section >30 MeV for ^{12}C, suggesting that neutron production in the carbon structure is a significant contributor. We also plot a differential power law spectrum with index −3.5. As is evident in Figure 4 the neutron yield from proton interactions at energies <30 MeV on ^{13}C is significant in the presence of such a steep spectrum and should have been included in the *Feldman et al.* [2010] calculations.

[45] We estimated the additional neutron yield from proton interactions below the 30 MeV neutron production threshold used by *Feldman et al.* [2010] by convolving the $E^{-3.5}$ proton spectrum with the total neutron production cross section of *Hua et al.* [2002]. We find that the total yield of neutrons would have been >3.8 times more than that calculated for protons with energies >30 MeV. About 75% of this increase is due to interactions on ^{13}C. We would expect to see a comparable if not greater increase if we limit the range of neutron energies to 0.5–7.5 MeV. Thus the yield of secondary neutrons from SEP protons after the safe hold period would have been at least 75% of the observed NS rate if the SEP event was dominated by protons.

[46] Low-energy solar energetic α particles interacting with the spacecraft can also produce secondary neutrons. This source of secondary neutrons was not considered by *Feldman et al.* [2010]. Significant fluxes of α particles have been observed in impulsive events associated with low M class X-ray flares [*Mason et al.*, 2002]. Interestingly, the onset times for neutrons and charged particles given by *Feldman et al.* [2010, Figure 4] are consistent with the arrival of 5 MeV nucleon^{-1} α particles. In addition durations of several hours for ~MeV nucleon^{-1} ions in impulsive SEP events are quite typical and similar to the duration of the neutron event. The neutron production threshold for α-particle reactions on ^{12}C is 2.8 MeV nucleon^{-1} while the α-particle reaction on ^{13}C is exothermic. Convolving an $E^{-3.5}$ alpha-particle spectrum with the total (α, n) cross sections on natural C [*Hua et al.*, 2002] we find that the neutron yield is about 100 times that for protons; therefore even for an SEP α/p ratio of 0.01 the neutron yield from α and proton interactions will be comparable. The total yield of neutrons from SEP interactions would then exceed the measured fast neutron rate observed by MESSENGER.

[47] Because the SEP spectrum measured in the December event before the safe hold (see section 5.1) appears to have been harder than the $E^{-3.5}$ power law assumed by *Feldman et al.* [2010], we reevaluated secondary neutron production using the neutron generation curve given by *Feldman et al.* [2010, Figure 8]. We find that for the harder SEP spectral index, −2.5, secondary neutrons could contribute ~35% to the observed fast neutron rate. If we now allow for both proton and α-particle neutron-producing interactions below

the 30 MeV nucleon^{-1} threshold assumed by *Feldman et al.* [2010] we estimate that the combined yield is less than for the softer spectrum but still exceeds the rate of fast neutrons observed by MESSENGER.

[48] We conclude that secondary neutrons from SEP p and α interactions in the spacecraft can account for the observed fast neutron rate (assuming that the SEP particles are mostly ions), based on what is described by *Feldman et al.* [2010], if neutron-producing interactions below 30 MeV are included. This can be confirmed by the MESSENGER team using their detailed MCNPX calculations.

6. Summary and Discussion

[49] The reported detection of 1–8 MeV neutrons from the 31 December 2007 solar flare by the MESSENGER NS at 0.48 AU [*Feldman et al.*, 2010] prompted us to both study the physics of low-energy neutron production in flares and evaluate the purported evidence for solar neutrons.

[50] We discussed the various neutron production channels from ion interactions in flares. Alpha-particle interactions dominate low-energy neutron production for incident particle energies below about 30 MeV nucleon^{-1} for plausible accelerated ion and ambient compositions. At higher incident energies, proton interactions contribute a growing fraction of the 1–10 MeV neutrons produced in solar flares. Due to exothermic reactions and the additional total energy associated with accelerated heavy ions, solar neutrons with energies above 10 MeV are produced even by accelerated ions with energies as low as 2 MeV nucleon^{-1}. In addition ions with energies of tens of MeV nucleon^{-1} and above are prolific producers of these low-energy neutrons. We showed that down-scattering in the spacecraft of these higher-energy solar neutrons from any plausible solar neutron spectrum could have produced fast neutron count rates that increased earlier than observed.

[51] Because low-energy neutrons are emitted roughly isotropically in the lab frame, many will move into higher densities of the solar atmosphere and produce the strong 2.223 MeV line when they form deuterium. If neutrons had been detected at the level implied by the MESSENGER observation of the 31 December 2007 flare, neutron capture γ rays would have been easily detected by instruments at Earth had the flare not been behind the solar limb. Without such a confirmation we can only use the MESSENGER data themselves to assess the plausibility of the reported neutron detection. We showed that the intense neutron signal observed by the NS over the 9 h observation period, if solar, required the acceleration at the Sun of ~10^{34} protons (>30 MeV) for a typical spectrum of flare ions. This number of protons is a factor of ten larger than that estimated for the largest γ ray line flare observed to date, the 4 June 1991 flare in which ~7×10^{32} protons were inferred [*Murphy et al.*, 1997].

[52] The 31 December event was classified only as a GOES M2 flare, a class of flare that is typically not a prolific producer of γ rays or neutrons; in contrast to the 4 June flare that was an X12 + flare. Typical X-ray flares with classifications lower than M5 produce neutron capture line fluences only ~0.1% of that implied by the *Feldman et al.* [2010] measurement. The 20 February 2002 event which the authors compare to the 31 December 2007 flare was a GOES M6 X-ray event with photon emission only extending up to ~25 keV in measurements made by RHESSI just after the peak. There was no evidence for significant γ ray emission that is typically associated with the production of neutrons in the 20 February flare. Surprisingly, the implied 2.223 MeV line fluence from the 31 December flare was comparable to the upper limit in the solar line fluence observed by the SMM spectrometer over a period of 4 years, excluding γ ray flares.

[53] A serious constraint on the reported neutron observation is that it suggests a total energy in accelerated ions of ~10^{34} erg (~5×10^{31} erg for a hard spectrum) over several hours. Because this ion energy would have to be dissipated in the solar atmosphere we would expect a comparable amount of energy to be emitted in thermal emission from the flare region. We estimate the expected energy in accelerated ions based on a comparison of the peak energy in the thermal X-ray plasma and energy in accelerated electrons, in this flare and two gamma ray flares [*Emslie et al.*, 2004]. This estimated ion energy is a factor of at least 50 below that inferred from the reported neutron observation. The GOES and MESSENGER measurements also show rapidly decaying soft X-ray emission following the M2 peak, typical of impulsive flares. Thus there is no evidence to support the presence of an intense flux of neutron-producing ions impacting the solar atmosphere over several hours.

[54] These solar physics arguments raise serious concerns about the reported detection of solar neutrons in the 31 December 2007 flare. The fact that the rise of the intense SEP event was coincident with the rise of the 1–8 MeV neutron signal is a serious concern, as is the similarity of their decay phase time profiles. If the SEP event contained a significant fraction of ions, the neutron counts may have been due to secondary neutrons from ion interactions in the spacecraft.

[55] *Feldman et al.* [2010] provide reasons why the SEP event was mostly composed of electrons which could not produce secondary neutrons. We argued that a failure in the EPS detector precludes such a conclusion. If protons comprised 100% of the solar energetic particles, *Feldman et al.* [2010] have concluded that secondary neutrons would have contributed no more than about 20% to the observed fast neutron rates after the safe hold period. This was based on detailed calculations using the spacecraft mass model and the MCNPX code assuming that the threshold for neutron production by protons is 30 MeV. The threshold is actually significantly lower for many of the materials, especially for the important carbon composite structure that contains about 1% ^{13}C. We estimated that for the power law proton spectrum with index −3.5 assumed by *Feldman et al.* [2010] the secondary neutron yield can be about a factor four higher than they calculated. We also discussed the significant role that low-energy α particles can play in the local production of neutrons. For a power law spectrum of α particles with the same index as the protons we found that they can produce a comparable number of neutrons even when the α/p ratio is 0.01. Thus it appears that SEP ion interactions in MESSENGER can account for most if not all of the observed neutron rate. We showed that this is also true for a harder ion spectrum with index −2.5.

[56] When all of these concerns are taken into account, we conclude that the reported detection of 1–8 MeV solar

neutrons from the 31 December 2007 flare at the inferred level is, at best, highly questionable. We provide compelling arguments that the fast neutron counts registered by MESSENGER originated from local neutron production by solar energetic protons and α particles.

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