Solar-Flare Particle Acceleration And Interaction Studies Using Gamma Rays

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SQ4: *Ion acceleration during impulsive flares*
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Our gamma-ray line studies reveal that the accelerated particles interacting in the solar atmosphere :

1) more generally reflect the heavy ion composition of gradual SEP events than impulsive SEP events.

2) the heavy ion to proton ratio is significantly higher than that observed in interplanetary space.

Framework of Study

All gamma-ray production codes have been brought up to date.

A variety spectroscopic fitting codes based on SSW OSPEX have been developed.

SMM/GRS, *RHESSI*, and *Fermi/GBM* flare data available in format compatible with OSPEX. Other data sets are limited spectroscopically or not available.

Due to radiation damage in *RHESSI* after the first year in orbit, the existing detector response function is only valid for the 2002 July 23 flare. This limits some spectral studies of the other flares.

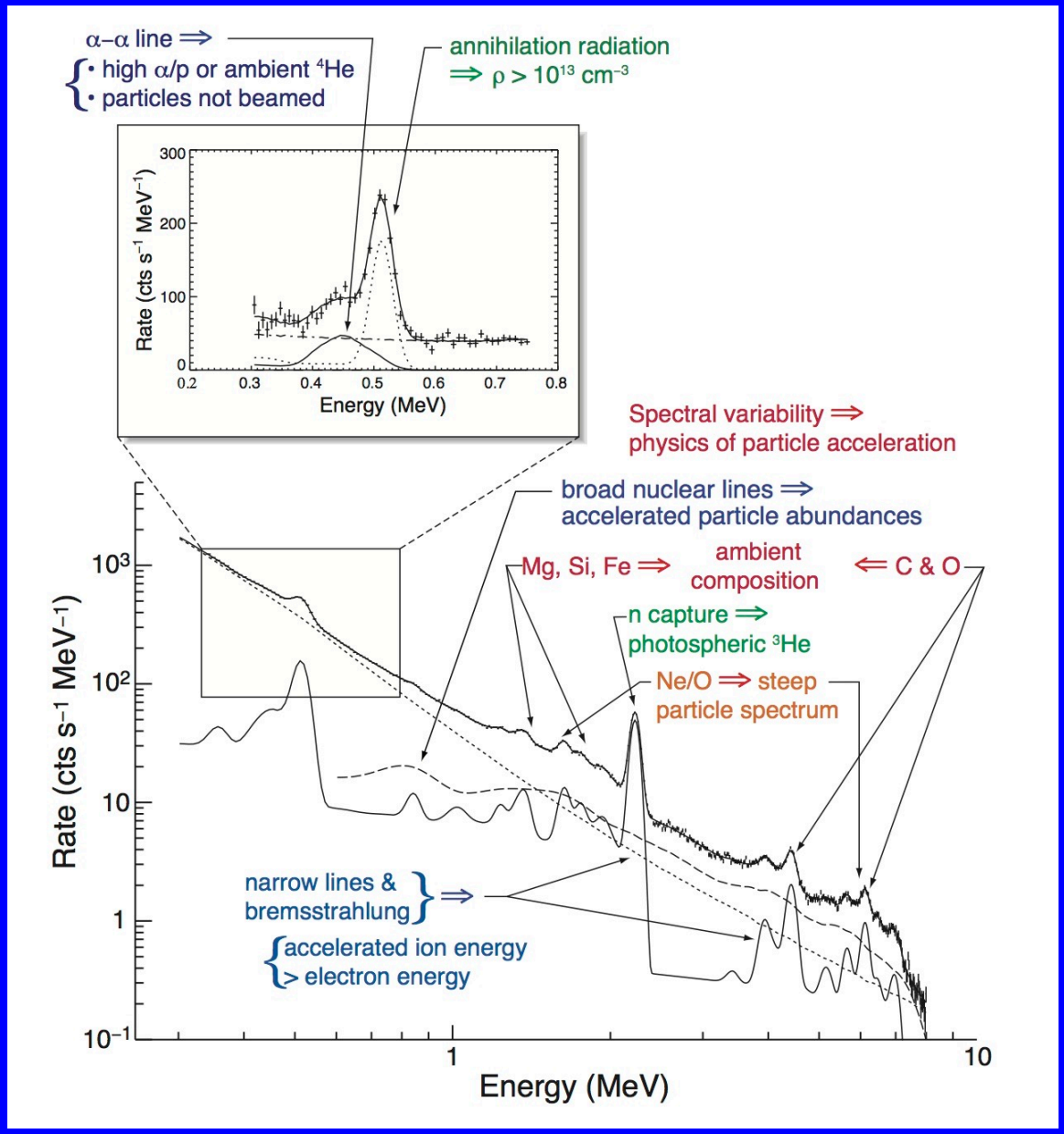
Limited spectral resolution of *Fermi/GBM* precludes its use for most studies.

The *SMM/GRS* detector response function revised using a Monte Carlo calculation. An instrumental artifact below the intense 2.2 MeV neutron capture line due to incomplete anti-coincidence coverage is accounted for in the fits to the data.

We study 19 *SMM/GRS* and 1 *RHESSI* flares.

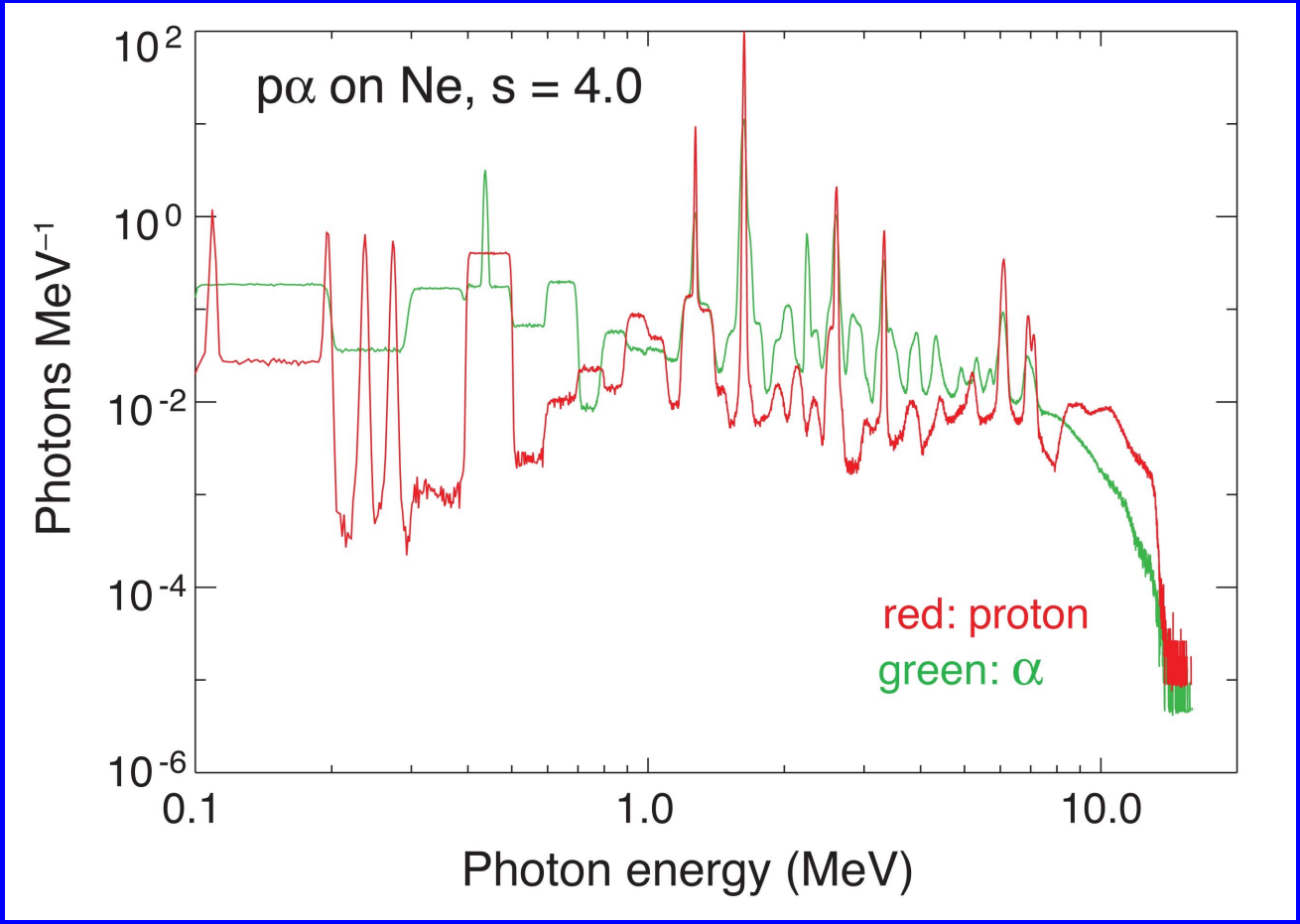
What γ-Rays Tell us About Accelerated Particles at the Sun

Summed γ-ray spectrum between 0.3 and 8 MeV from 19 solar flares observed by SMM. The contributing components are identified: electron bremsstrahiung, narrow nuclear lines from p's and α's, broad lines from heavy ions, e^+-e^- annihilation line, neutron capture line, and α–α fusion lines.



Example of a nuclear line template used in our spectral fits

Prompt de-excitation lines produced by p and α interactions on ^{20}Ne



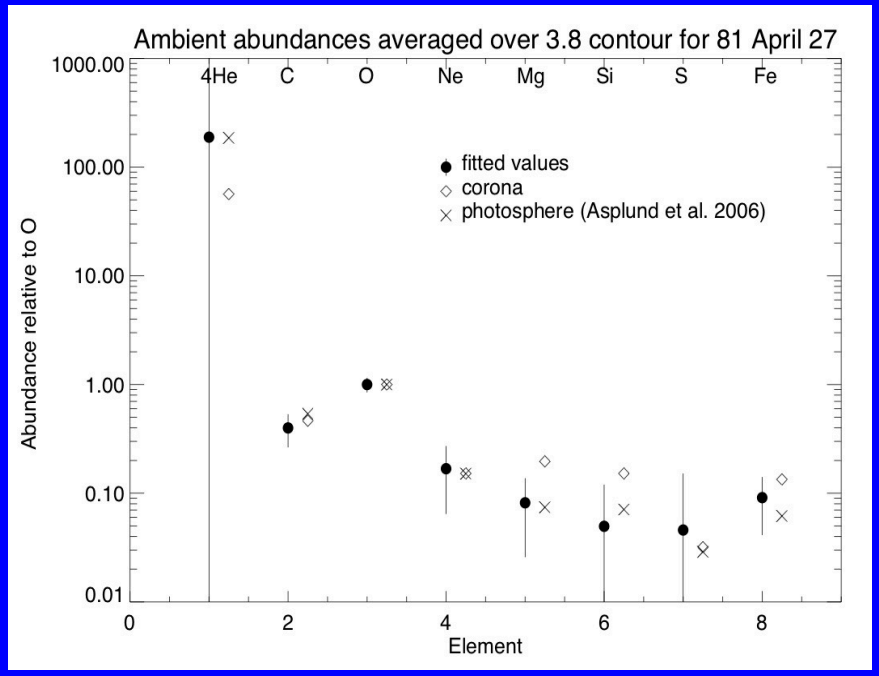
Two sets of fits were done on each flare:

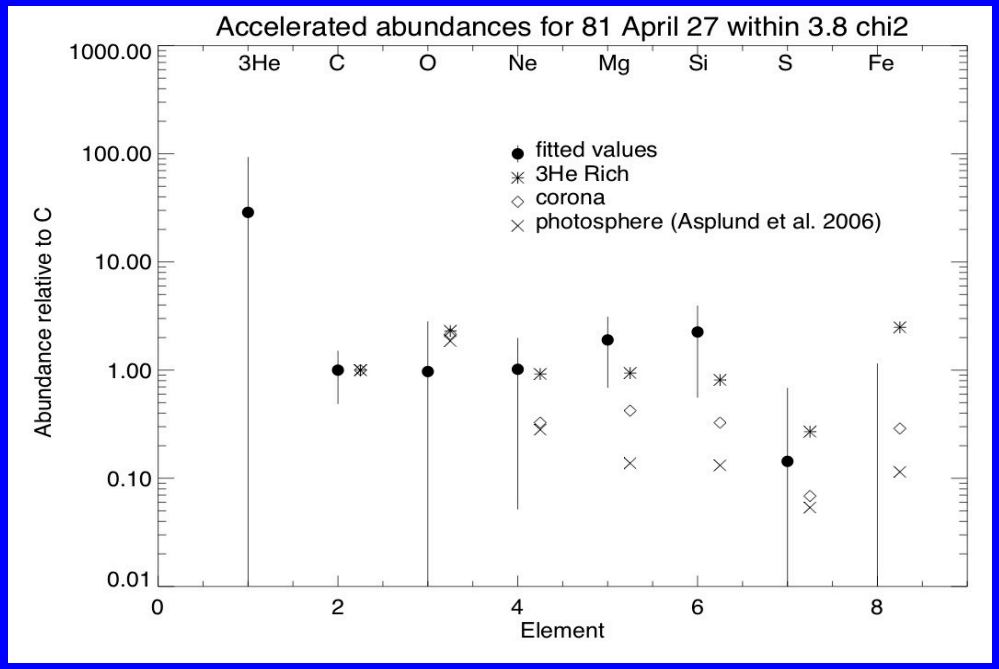
Abundance fit: Individual C, O, Ne, Mg, Si, S, and Fe line templates for both direct (p and α on ambient material) and inverse (heavy nuclei on ambient H and He) interactions.

Composition fit: Combined templates of the elements for different assumed compositions (e.g. coronal) for both direct and inverse reactions. This improves statistics for fits to weak flares.

Results of two fits generally are consistent but there are differences that we need to resolve.

Ambient and Accelerated Abundance Study



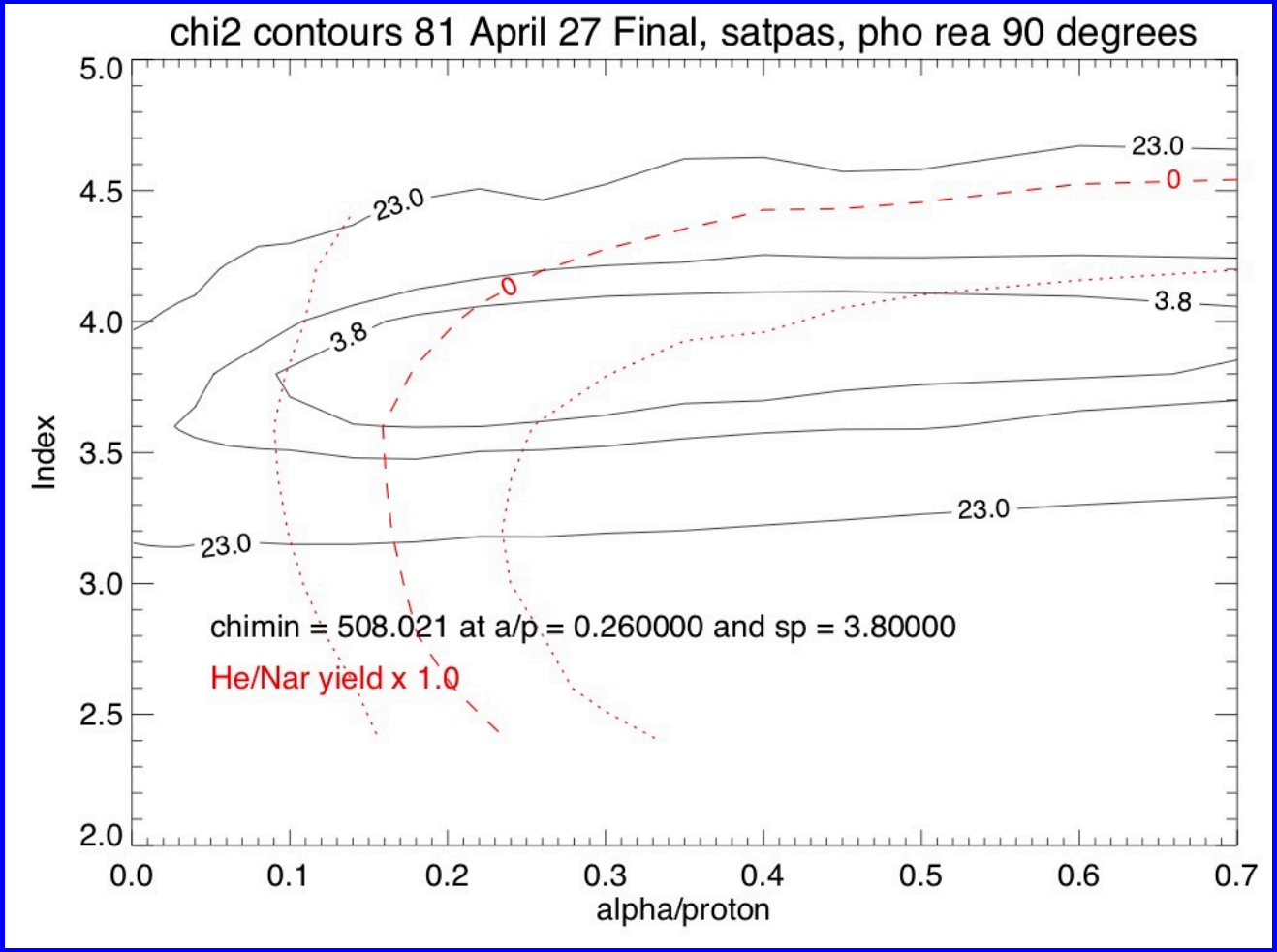


Ambient elemental abundances relative to O (left panel) and accelerated elemental abundances relative to C (right panel) compared to plausible compositions.

Relative ambient composition is best fit by a photospheric composition. Either a coronal or impulsive SEP composition can fit the relative accelerated ion abundance.

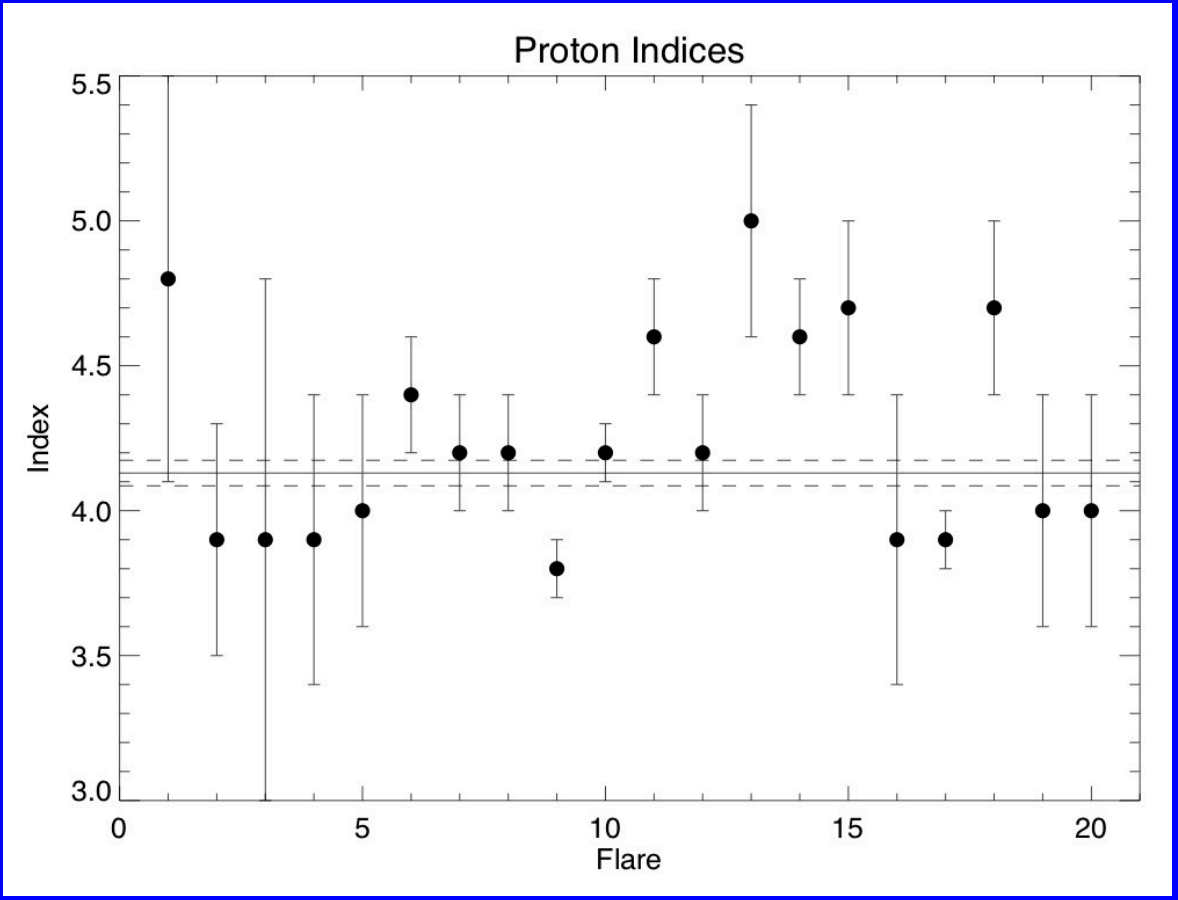
χ^2 map of fits to flare spectrum

3.8 = 1 σ contour



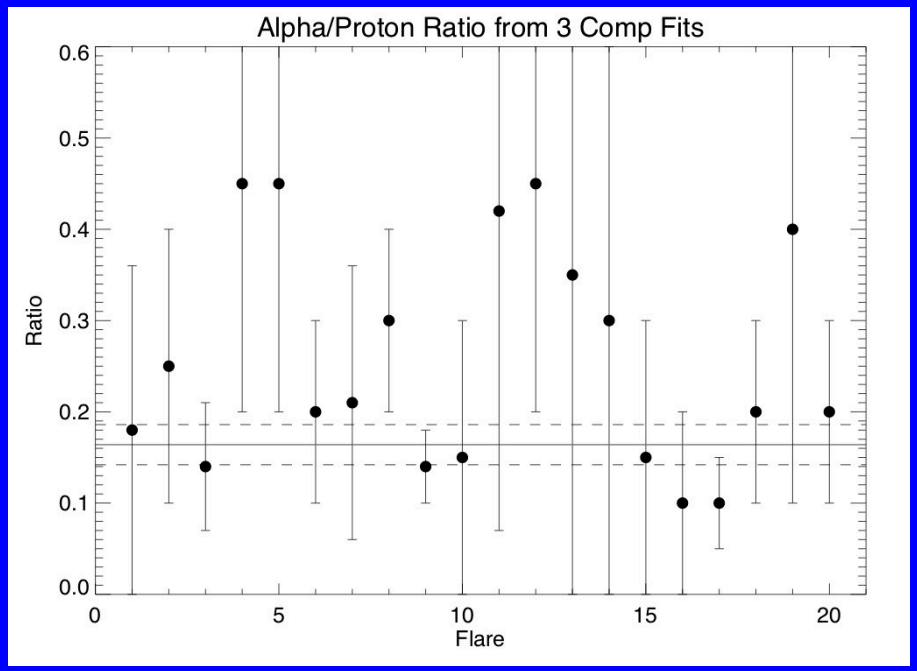
Spectral fits constrain the proton spectral index (power-law) well but not the accelerated α/p ratio. An additional constraint on this ratio comes from the flux in the α-^{4}He lines (shown by red curves).

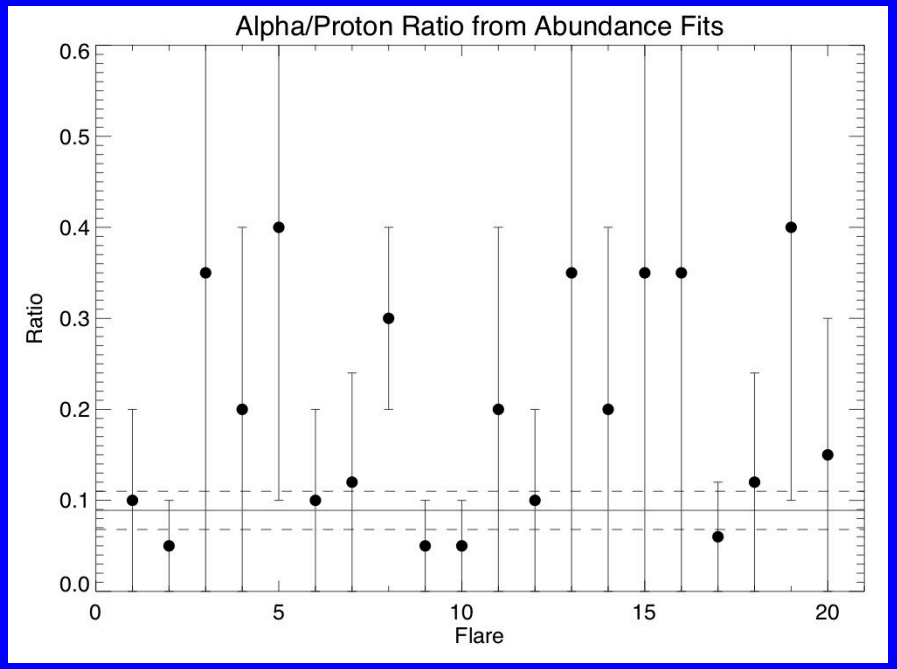
Accelerated Proton Power-Law Spectral Indices



Accelerated particle power index ranges from ~3.5 to 5 with a weighted mean of 4.15 +- 0.05

Accelerated α/p Ratios





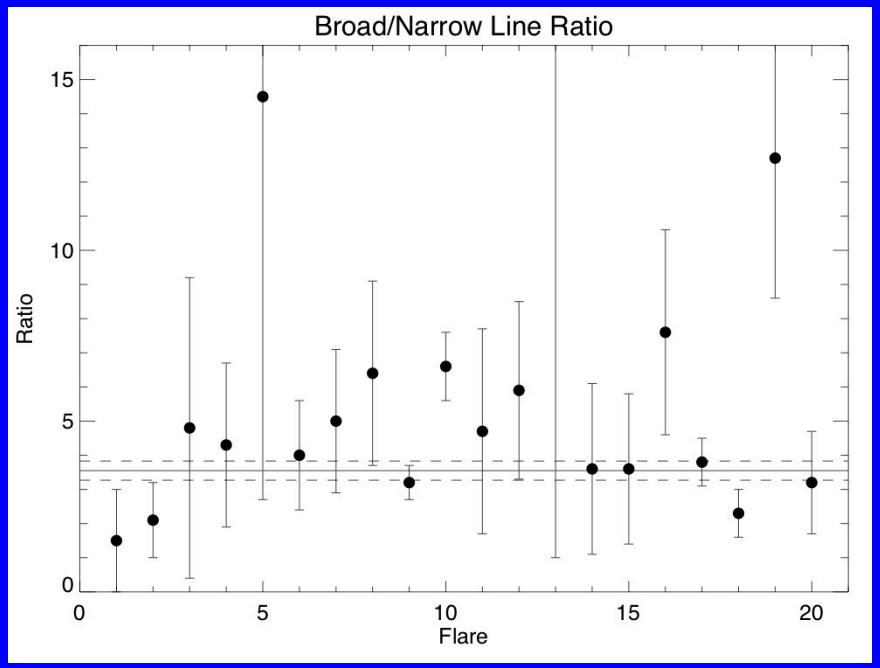
α/p ratios using composition (left) and abundance (right) fits.

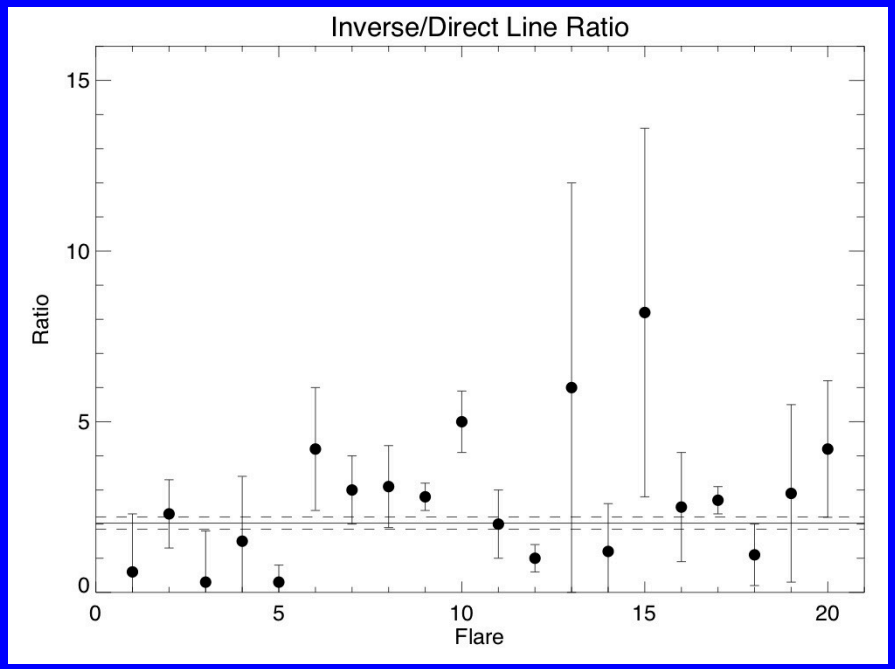
At present the determination of the ratio and uncertainties is subjective and needs to be improved.

The weighted means of the α/p ratios are:

Composition fit	0.16 +- 0/02
Abundance fit	0.09 +- 0.02
Photospheric ^{4}He/H	0.085
Coronal	0.036

Accelerated Heavy Ion/(p + α) Ratio





We determine the ratio of the number of accelerated heavy ions (>α particles) to the number of accelerated α and p's for the assumed abundances. We use the composition (summed elements) method (left panel) and the abundance method (right panel). We expect a ratio of unity for both methods for the assumed abundances. We obtain weighted mean ratios of:

Composition method: 3.5 +- 0.3

Abundance method: 2.0 +- 0.2

The heavy elements in the flare accelerated particles appear to be enhanced over what is expected for a gradual or impulsive SEP composition.

Results on Flare-Accelerated Particles from Gamma-Ray Spectroscopy

The flare-accelerated particle power-law index ranges from ~3.5 to 5, with a weighted mean of 4.15 +- 0.05, between ~3-30 MeV/nucl.

Of the 20 flares studied, 8 are best fit by heavy accelerated particles with a gradual SEP composition, 1 by an impulsive SEP composition, 10 for which we cannot distinguish the composition that is the best, and 1 which is not well fit by either.

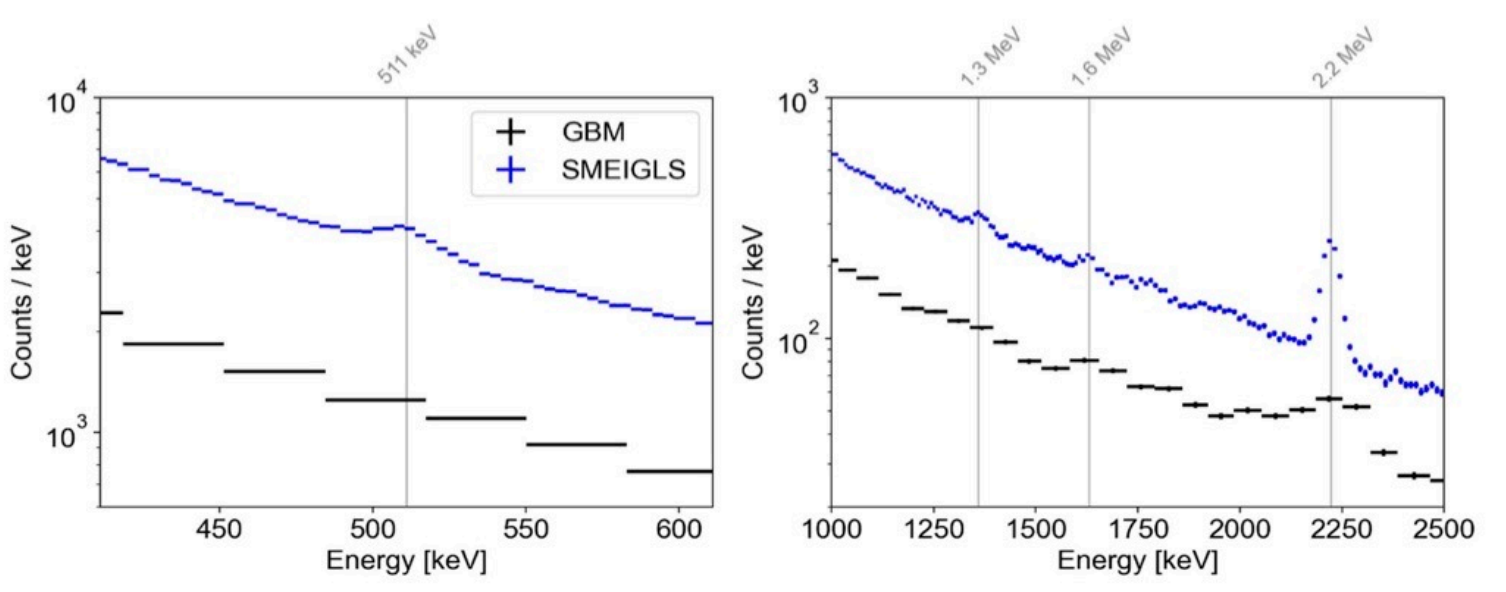
The flare-accelerated α/p ratio is significantly enhanced over the average ratio of 0.036/0.046 observed in gradual/impulsive SEP populations of accelerated particles.

Elements with Z>2 are significantly enhanced relative to protons in the flare accelerated ion population compared to what is observed in gradual or impulsive SEP populations.

This suggests a strong Q/A dependence in the acceleration and transport processes for particles interacting at the Sun.

There appears to be significant temporal variation in the heavy ion/proton ratio that requires further study.

No Gamma-Ray Mission in Orbit with Spectroscopic Capability Necessary for Flare Studies in Cycle 25. Mission Proposed for Space Station in 2025.



Comparison of proposed SMEIGLS experiment with Fermi/GBM

	511 keV		2.2 MeV	
	Photopeak area	**FWHM resolution**	**Photopeak area**	**FWHM resolution**
SMEIGLS	268 cm^2	24 keV	135 cm^2	49 keV
Fermi/GBM†	120 cm^2	70 keV	40 cm^2	150 keV
RHESSI††	27 cm^2	2 keV	19 cm^2	4 keV
SMM/GRS	175 cm^2	41 keV	66 cm^2	85 keV