\section*{\textcolor{blue}{Yohkoh}}

\section*{RHESSI}

\textbf{γ-ray and Neutron Production in Solar Flares}

\begin{itemize}
  \item magnetic reconnection
  \item corona e, p, $^3$He, $\alpha$, C, N, O, ...
  \item γ-ray and Neutron Production in Solar Flares
  \item $t_{\text{dur}}$ = 10’s of minutes
\end{itemize}

\textbf{reaction products}

\textbf{chromosphere}

\begin{itemize}
  \item $2218-2228$ keV
  \item $70-100$ keV
\end{itemize}
Products of Accelerated-Particle Interactions

Products of ion nuclear interactions

- excited nuclei
- radioactive nuclei
- neutrons
- $\pi^+, \pi^-, \pi^0$

Observable emission

- $e^-$: X- and $\gamma$-ray bremsstrahlung

- ions:
  - excited nuclei $\rightarrow$ prompt $\gamma$-ray line radiation
  - radioactive nuclei $\rightarrow$ delayed $\gamma$-ray line radiation
    - $e^+ \rightarrow \gamma_{511}$ & continuum
  - neutrons $\rightarrow$
    - escape into space (and n-decay protons & electrons)
    - capture on H $\rightarrow$ d + $\gamma_{2.223}$
    - $\pi^0 \rightarrow 2\gamma$ \quad $m_{\pi^0} = 135$ MeV $\rightarrow \varepsilon_\gamma = 67.5$ MeV
    - $\pi \rightarrow \pi^+\gamma \rightarrow e^+\gamma$ (annihilation, line & in-flight continuum)
    - continuum emission via bremsstrahlung
Deexcitation-line Spectrum

Narrow-line (2% FWHM) ratios: ambient composition
Broad-line (20% FWHM) ratios: accelerated-ion composition

Photon energy (MeV)

Photons MeV⁻¹

56Fe 24Mg, 20Ne, 28Si 12C 16O

s = 4

4.438 MeV 12C line
Isotropic accelerated-particle angular distribution

“lab” energy 4.438 MeV 

p + 12C "narrow" line

12C + p "broad" line
\[ \varepsilon = 67.5 \text{ MeV} \] (\( m_{\pi^0} c^2/2 \))

- \( s_p = 3 \)
- \( N_p(>30 \text{ MeV}) = 1 \)
- \( B = 300 \text{ G} \)
- \( n_H = 1 \times 10^{15} \text{ cm}^{-3} \)
- \( ^4\text{He}/H = \alpha/p = 0.1 \)

**Photons MeV\(^{-1}\)**

**Sensitive to shape of >300 MeV ion spectrum**
Annihilation Line and Neutrons

$\ n_H = 10^9 \ cm^{-3}$
$\ T = 5000 \ K$
$\ 100\% \ neutral$

[Graph showing photon energy distribution with labels for ifce, total, 3ν continuum, thermal ce, dab (H), and dab (He).]

[Graph showing time (UT sec on 4 June 1991) vs. neutron count rate, deexcitation-line flux (arbitrary units), and unbroken PL with high-energy cutoff.]
Total Gamma-ray Spectrum

\[ s = 4 \]
\[ n_H = 1 \times 10^{15} \text{ cm}^{-3} \]
\[ B = 300 \text{ G} \]
\[ \theta_{\text{obs}} = 60^\circ \]

- n-capture
- deexcitation lines
- \( \pi \) decay
- \( e^- \) bremsstrahlung

[Graph showing the total gamma-ray spectrum with various labeled features and data points.]
Solar-flare Gamma-ray Observations

2010 June 12

Flux (photons cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\))

Energy (MeV)

- 2010 June 12

Solar-flare Gamma-ray Observations
Cross Sections and Ion-energy Dependences

Production cross sections for proton reactions

Radiation
- deexcitation lines: 2–20 MeV nucleon\(^{-1}\)
- n-capture: 10–30 MeV nucleon\(^{-1}\)
- neutrons @ Earth: >30 MeV nucleon\(^{-1}\)
- \(\pi\)-decay: \(\approx 300\) MeV nucleon\(^{-1}\)

Ion energy
- 2–20 MeV nucleon\(^{-1}\)
- 10–30 MeV nucleon\(^{-1}\)
- >30 MeV nucleon\(^{-1}\)
- \(\approx 300\) MeV nucleon\(^{-1}\)
Ion Spectral Shape from Emission Ratios

$\theta_{\text{obs}} = 60^\circ$

- $Q_{\pi}(>100 \text{ MeV})/Q_{2.2}$
  - $[>300 \text{ MeV}]$ — $[10–30 \text{ MeV}]$

- $Q_{2.2}/Q_{4.4}$
  - $[10–30 \text{ MeV}]$ — $[5–15 \text{ MeV}]$

- $Q_{6.1}/Q_{1.6}$
  - $[10–20 \text{ MeV}]$ — $[2–10\text{MeV}]$
Deriving Ion Spectral Index from Fermi LAT and GBM Data

**2010 June 12 flare**  

- n-capture deex lines: $s_1 = 3.2$
- $\pi$-decay: $s_2 = 4.3$
- $\pi$-decay spectral shape: $s_3 > 4.5$

![Graph](image-url)
Long-duration Events

High-energy emission continues long after the impulsive phase

2011 March 7 flare
Ackermann, et al. 2014
G. Share (priv. comm.)

Flux (photons cm\(^{-2}\) s\(^{-1}\))

LAT >100 MeV
RHESSI/GBM (renormalized)
Source of Long-duration Emission

- Continuous acceleration in a flare loop
- Impulsive acceleration – trapping
- CME/shock acceleration – precipitation

2012 Mar 7 emission for 20 hr.
Ajello, et al. 2014

2013 Oct 11 over-the-limb flare
Pesce-Rollins, et al. 2015 (in prep.)