Time Evolution Observation of De-excitation Line Shapes in Solar Flare

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Introduction

- **Solar de-excitation lines**, produced from nuclear reactions of accelerated ions interacting with solar atmospheric media, are the most direct diagnosis of the accelerated ions.

- How to derive the ion’s information?
  - Estimate the fluency ratio of the 4-7 MeV band to the neutron capture lines (Murphy & Ramaty, 1984; Murphy et al. 2007).
  - Spectroscopic fit the whole gamma-ray spectrum (Chen & Gan, 2012).

- The lines shapes, include energy shifts and width of lines, reveal the angular distribution of the interacting ions (Ramaty & Crannell 1976). Smith (2003) report the first measurements of de-excitation lines shapes by the RHESSI.
Spectral line shapes calculation

1. Recoil nucleus emit isotropically in the CM frame;
2. Isotropic gamma-ray emissions in the excited nucleus rest frame

\[ v_{tx} = \frac{v_{tcm} \cos(\theta_{cm}) + v_{cm}}{1 + v_{tcm} \cos(\theta_{cm}) \cdot v_{cm}} \]
\[ v_{ty} = \frac{v_{tcm} \sin(\theta_{cm})}{\gamma(1 + v_{tcm} \cos(\theta_{cm}) \cdot v_{cm})} \]

\[ \nu_{res} = \sqrt{v_{tx}^2 + v_{ty}^2} \]
\[ \theta = \tan^{-1}\left(\frac{v_{tx}}{v_{ty}}\right) \]

\[ E_\gamma = E_0 / \gamma (1 - \beta_{res} \cos \theta) \]
\[ = E_0 (1 + \beta_{res} \cos \theta) \quad \gamma \ll 1 \]
Shapes of $^{20}$Ne line

Calculated shapes of r-ray lines from the de-excitation of 20Ne relative to: (left) the isotropic incident ions for the various spectrum, (right) and the different flare location with downward-isotropic ions.
Property of $^{20}$Ne line shapes (FWHM, Redshift)

Property of 1.634 MeV line shapes varied with the spectral index (s) and $a/p$ for downward-isotropic ions at flare sites near the center of the Sun. Left: line width (FWHM); Right: center energy shift.
Analysis of observation data

- 2002 Jul 23 X4.8 event, 00:27:20-00:39:56
- S13 E72, heliocenter angle ≈ 73°
Solar de-excitation lines spectrum for ions index of 4.0 and alpha-to-proton ratio of 0.1. Blue curve represent the whole spectrum exclude the lines of Fe 0.847 MeV, Mg 1.369 MeV, Ne 1.634 MeV, Si 1.779 MeV, C 4.438 MeV and O 6.129 MeV. (Chen & Gan, 2011)
Fitting results for different templates of de-excitation lines spectrum

$s=2.0 \ a/p=0.1$ Downward-Isotropic at Heliocentric Angle of 70°

$s=4.0$
- Best-fit gaussian parameters for lines

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Rest energy (keV)</th>
<th>Fit energy (keV)</th>
<th>% Redshift</th>
<th>FWHM (keV)</th>
<th>% FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>4438</td>
<td>4405 ± 9</td>
<td>0.74 ± 0.20</td>
<td>89 ± 19</td>
<td>2.01 ± 0.43</td>
</tr>
<tr>
<td>O</td>
<td>6129</td>
<td>6105 ± 17</td>
<td>0.39 ± 0.28</td>
<td>107 ± 34</td>
<td>1.75 ± 0.55</td>
</tr>
<tr>
<td>Ne</td>
<td>1634</td>
<td>1628.6 ± 1.5</td>
<td>0.33 ± 0.10</td>
<td>21.9 ± 3.6</td>
<td>1.34 ± 0.22</td>
</tr>
<tr>
<td>Mg</td>
<td>1369</td>
<td>1366.3 ± 2.7</td>
<td>0.20 ± 0.20</td>
<td>33.6 ± 6.5</td>
<td>2.45 ± 0.47</td>
</tr>
<tr>
<td>Si</td>
<td>1779</td>
<td>1779.2 ± 2.9</td>
<td>-0.01 ± 0.16</td>
<td>37.6 ± 6.7</td>
<td>2.11 ± 0.38</td>
</tr>
<tr>
<td>Fe</td>
<td>847</td>
<td>846.8 ± 0.7</td>
<td>0.04 ± 0.08</td>
<td>3.0 ± 3.3</td>
<td>0.36 ± 0.40</td>
</tr>
</tbody>
</table>

Smith, 2003
The comparison of line shapes property between measurements and calculations.

Thick horizontal line: measure from us;
Thin horizontal line: measure from Smith (2003)

Heliocentric Angle = 70°
Heliocentric Angle = 40°
Downward isotropic injection

Beam injection
Discussion

De-excitation line shape analysis method is a new window for studying ion’s property.

- NOT rely much on the fitting model of whole spectrum
- WITH abundant lines observations
- POOR count rate and sensitivity in observation
- EXISTENCE of multiple solutions of one fitting parameter.

e.g. Combine α-α line ($^7\text{Be}^{0.429} \rightarrow \text{g.s.}$, $^7\text{Li}^{0.478} \rightarrow \text{g.s.}$)
The observation redshifts of C, O and Ne lines are larger than theoretical calculation for a model of interacting ions with downward-isotropic in a radial magnetic field. Beam injection of accelerated ions or tilt of the magnetic field to the solar surface?

The results of ions property by analyzing different lines shape are not completely consistent. The property of accelerated ions is varied as flare evolution.
Thanks for your attention!