Radioresistance of adenine to cosmic rays

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Introduction

• The presence of complex organic molecules (COM) such as nucleobases and amino acids in carbonaceous meteorites on Earth is a strong indication of its existence in outer space. †.

• Detection of glycine (amino acid) in the coma of comet 67P/Churyumov-Gerasimenko by the Rosetta space mission*. 

• Some groups have reported formation of COM under simulated astrophysical environments˚.

• Stability of COM under irradiation of galactic cosmic rays and solar wind is not yet well understood.

Objective

- To simulate and study effects of cosmic rays (swift heavy ions) of COM by using the beam line at GANIL and GSI.

First results: irradiation of adenine.
Adenine

- C₅H₅N₅
- A purine nucleobase
- An integral part of the composition of biomolecules of unique importance such as DNA and RNA
- A molecule that is evolutionarily preserved in all living beings, including viruses.
Experimental methodology

Low temperature (\( \sim 12 \text{ K} \)).

10^{-8} \text{ mbar}.

Adenine sample prepared for irradiation.
Swift Heavy Ions – Cosmic rays analogues

Cosmic rays are ions with a broad energy range from few MeV/n to TeV/n.

Complex molecules have complex IR spectra.

Solid adenine spectrum at 12K

\[ N = \frac{2.3}{A} \int Abs(\nu) \, d\nu \]
## Summary of performed experiments

<table>
<thead>
<tr>
<th>Ion Beam</th>
<th>Energy (MeV/u)</th>
<th>Electronic stopping power (keV.µm⁻¹)</th>
<th>Nuclear stopping power (keV.µm⁻¹)</th>
<th>Thickness (µm)</th>
<th>Penetration depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe⁺²³</td>
<td>0.7</td>
<td>1.12 x 10⁴</td>
<td>6.95 x 10¹</td>
<td>0.29</td>
<td>16</td>
</tr>
<tr>
<td>Kr³³⁺</td>
<td>10.5</td>
<td>5.80 x 10³</td>
<td>3.6</td>
<td>0.50</td>
<td>120</td>
</tr>
<tr>
<td>Ca¹⁰⁺</td>
<td>4.8</td>
<td>3.3 x 10³</td>
<td>2.22</td>
<td>0.35</td>
<td>50</td>
</tr>
<tr>
<td>C⁴⁺</td>
<td>0.98</td>
<td>1.00 x 10³</td>
<td>0.9</td>
<td>0.25</td>
<td>12</td>
</tr>
</tbody>
</table>
Results – IR spectra evolution

$Xe^{23+}$ (92 MeV)
Results – IR spectra evolution

New molecules produced by fragmentation of adenine.

Fluence [ions.cm$^{-2}$]
- 0
- $5 \times 10^{10}$
- $2 \times 10^{11}$
- $6 \times 10^{11}$
- $2 \times 10^{12}$

$\text{Xe}^{23+}$ (92 MeV)

914 cm$^{-1}$

Absorbance

Wavenumber (cm$^{-1}$)

900 1000 1100 1200 1300 1400 1500 1600 1700

Absorbance

Wavenumbers (cm$^{-1}$)

2044 cm$^{-1}$

2070 cm$^{-1}$

2090 cm$^{-1}$

2100 cm$^{-1}$

2124 cm$^{-1}$

2147 cm$^{-1}$

2173 cm$^{-1}$

2212 cm$^{-1}$

2240 cm$^{-1}$

2262 cm$^{-1}$

2300 2290 2280 2270 2260 2250 2240 2230 2220 2210 2200 2190 2180 2170 2160 2150 2140 2130 2120 2110 2100 2090 2080 2070 2060 2050 2040 2030 2020 2010 2000

Spectrum

Fit

C$_2$H$_4$N$_4$

R-CN

CN

HCN

R-NC

C$_2$H$_2$N$_2$
Results - IR spectra evolution

\[ A = A_0 e^{-\sigma_d F} \]

<table>
<thead>
<tr>
<th>Sample</th>
<th>Destruction cross section ( (x10^{-13} \text{ cm}^2) )</th>
<th>( S_e ) ( [x10^3 \text{ keV \mu m}^{-1}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe ( ^{23+} )</td>
<td>22.1 ± 0.1</td>
<td>11.2</td>
</tr>
<tr>
<td>Kr ( ^{33+} )</td>
<td>11.4 ± 0.3</td>
<td>5.8</td>
</tr>
<tr>
<td>Ca ( ^{10+} )</td>
<td>4.5 ± 0.2</td>
<td>3.3</td>
</tr>
<tr>
<td>C ( ^{4+} )</td>
<td>1.24 ± 0.06</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Results

Cross section as a function of stopping power.

\[ \sigma = 4 \times 10^{-17} S_e^{1.17} \]

Results obtained by our group show that the destruction cross section obeys an electronic stopping power law with:

\[ 1 \leq n \leq 1.5 \]
Results

Destruction cross section

Flux:

\[ \Phi(Z, E) = \frac{C(Z) E^{0.3}}{(E + E_0)^3} \]

\( E_0 = 400 \text{ MeV/n} \)

Results

Destruction rate

\[ \Phi \times \sigma \] [s^{-1} sr^{-1} (MeV/n)\(^{-1}\)]

Energy [MeV per nucleon]

\(E_0 = 400\) MeV/n
Results

Half-life of solid adenine exposed to cosmic rays in the ISM.

\[
\tau_{1/2} = \ln 2 \left( 4 \pi \sum_Z \int \sigma(Z,E) \Phi(Z,E) \, dE \right)^{-1}
\]

\[
\tau_{1/2} = (10 \pm 8) \times 10^6 \text{ years}
\]

The average time of survival of a DC is around 10 Myears. This is indeed close to the order magnitude of the half-life of adenine evaluated in this work.
Results

Comparision between different sources of radiation

The radiation G yield is defined as the number of adenine molecule destroyed per 100 eV absorbed.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Radiation yield G (eV⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe²³⁺ (92 MeV)</td>
<td>13.13</td>
<td>This work</td>
</tr>
<tr>
<td>Kr³³⁺ (820 MeV)</td>
<td>12.56</td>
<td>This work</td>
</tr>
<tr>
<td>Ca¹⁰⁺ (192 MeV)</td>
<td>9.70</td>
<td>This work</td>
</tr>
<tr>
<td>C⁴⁺ (12 MeV)</td>
<td>8.29</td>
<td>This work</td>
</tr>
<tr>
<td>Electrons (5 keV)</td>
<td>1.98</td>
<td>(Evans et al., 2011)</td>
</tr>
<tr>
<td>UV photons</td>
<td>4.9 × 10⁻⁵</td>
<td>(Guan et al., 2010; Saïagh et al., 2014)</td>
</tr>
</tbody>
</table>
Results

Half-life of solid adenine exposed to different source of radiation in distinct regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>UV photons</th>
<th>Cosmic Rays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Half-life (Myears)</td>
<td>UV flux (cm^{-2} s^{-1})</td>
</tr>
<tr>
<td>ISM</td>
<td>4.5 x 10^{-1}</td>
<td>1.0 x 10^{8}</td>
</tr>
<tr>
<td>Dense Clouds (DC)</td>
<td>4.5 x 10^{4}</td>
<td>1.0 x 10^{3}</td>
</tr>
</tbody>
</table>
Conclusions

• The adenine molecule destruction cross sections as a function of the deposited energy follow a power law: $A S_e^n$ with $n = 1.17$

• The destruction of solid adenine by cosmic rays are dominated by iron and protons.

• The half-life of adenine was estimated in different region of space: ISM (0.45 Myears) and DCs (10 Myears).
Outlooks

- Irradiation of the all nucleobases that composes DNA and RNA. (Thymine, Uracil, Guanine and Cytosine).

- Improvement of the methodology of preparation of solid nucleobases: films more uniform.

- Irradiation of Pyridine, a important heterocyclic biomolecule using complementary techniques: IR spectroscopy and time of flight.

- Data under analysis.
Thank You for your attention!

Q&A

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