The GEM scintillation in He-$CF_4$, Ar-$CF_4$, Ar-TEA and Xe-TEA mixtures


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Summary

• Motivation
• Experimental set-up
• Emission spectra of Ar/CF$_4$ and He/CF$_4$.
• Excitation and de-excitation processes in CF$_4$ and CF$_4$ mixtures
• Emission spectra of Ar/TEA
• Total light yields
• Conclusions

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The GEM - gas electron multiplier

See http://gdd.web.cern.ch/GDD/

Magnitude of the electric field along the center of the GEM channel.

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Applications
(with CCD readout of the GEM scintillation)

• Alpha particle tracking:
  Triple GEM with Ar+40%CF₄
  $^{241}$Am $\alpha$ particles $E = 5.48$ Mev
  Range in Ar = 3.42 cm

• Thermal neutron detection:
  Proton and triton tracks in $^3$He- 400 mbar CF₄
  Triple GEM
  AmBe source with Polyethylene shielding
  *(F. Fraga et al., NIM A 478 (2002) 357)*
Applications

- X-ray imaging
- Car key ~5 cm radiography
- X-ray energy ~8keV
- Xe-10%CO$_2$ at 1bar
- absorption length ~3 mm
Objectives:

• measure the emission spectra of Ar- and He-CF$_4$ mixtures and identify the main emitting channels.
• quantify the total light yields;
• study other gas mixtures leading to a stable operation of the GEM detector and exhibiting large photon yields either in the visible and near infrared (NIR) or in the UV region.
Experimental set-up

Detection system

X rays from:
- Fe-55 source (5.9 keV);
- X-ray generator

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Detection systems

• Total light yields:
  ‣ Planar-diffused silicon photodiode (UDT PIN-25DP)
    \[ \frac{N_{ph}}{e^-} = \frac{I_{ph}}{I \cdot Q \cdot e \cdot T \cdot \frac{\Omega}{4\pi}} \]
    \( \sigma < 15\% \)
  ‣ Photomultiplier (56 TUVP) (operating in the pulse mode)
    \[ \frac{N_{ph}}{e^-} = \frac{f_c \bar{q}}{\frac{\Omega}{4\pi} \cdot M \cdot T \cdot N_e} \]
    \( \sigma < 30\% \)

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• **Emission spectra:**

  ‣ **Monochromator (Applied Photophysics m. 7300, with a 1200 g/mm grating blazed at 500 nm) + photomultiplier (RCA C31034), cooled to -20°C, operating in single photon counting mode.**

  ‣ **Spectral sensitivity of the detection system is measured with:**

    ➔ **Standard tungsten strip lamp (Osram WI 17/G)**
    
    $\lambda > 310$ nm, previously calibrated against a black body (*in Institute of Physics, Belgrade*)

    ➔ **Deuterium lamp (200 - 370 nm);**  

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Spectroradiometric calibration with the tungsten strip lamp

Calibration factor:

\[ Q(\lambda) = \frac{N_0(\lambda)}{S(\lambda)} \]
• Nº of photons entering the monochromator per second:

\[ S(\lambda) = \varepsilon(T, \lambda) \cdot N_c(T, \lambda) \cdot \Delta A \cdot \Omega_E \cdot \Delta \lambda \cdot f(\lambda) \]

\[ \Omega_E \] is the effective solid angle;

\[ \Delta A \] effective emitting area of the tungsten ribbon;

\[ \varepsilon(T, \lambda) \] emissivity of tungsten;

\[ N_c(T, \lambda) \cdot \Delta \lambda \] nº of photons emitted per unit time, per unit area and per steroradian, by a blackbody at a temperature T, in the wavelength range between \( \lambda \) and \( \lambda + \Delta \lambda \)

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Charge Gains

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<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ar</th>
<th>CF₄</th>
<th>Xe</th>
<th>TEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. P. (eV)</td>
<td>24,58</td>
<td>15,7</td>
<td>15,9</td>
<td>12,12</td>
<td>7,51</td>
</tr>
<tr>
<td>E_{exc} (eV)</td>
<td>19,82</td>
<td>11,54</td>
<td>12,5</td>
<td>8,4</td>
<td>4,77</td>
</tr>
</tbody>
</table>
Emission spectrum of Ar+5%CF$_4$ mixture

$G = 40; \quad \Delta \lambda = 4 \text{ nm (raw data)}$

- CF$_3^*$
  - $(1E', 2A_2'' \rightarrow 1A_1')$
- OH$^-$
- Ar I
  - 2p→3s lines

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Visible and NIR emission spectra of Ar-CF$_4$ mixtures, normalized to the light intensity at 620 nm.

Nº of photons emitted, between 400 and 1000 nm, per secondary electron, as a function of the effective gain, in Ar-CF$_4$ mixtures. (Measurements performed with the photodiode).

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Emission spectra of He-CF$_4$ mixtures

He+20% CF$_4$ : $G = 335$
He+40% CF$_4$ : $G = 175$
$\Delta\lambda = 4$ nm

Emission spectrum of He+40%CF$_4$, corrected for 2$^{nd}$ order diffraction effects and the quantum efficiency of the detection system.
He-CF$_4$ mixtures

Light intensity, normalized to the current, measured for $\lambda = 620$ nm, as a function of CF$_4$ concentration.

Visible emission spectra of He-CF$_4$ mixtures, measured with a glass color glass filter ($\lambda_{cut-off}=435$ nm).
**CF$_4$**

<table>
<thead>
<tr>
<th>Process</th>
<th>Threshold (eV)</th>
<th>Energy loss (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct vibrational excitation $\nu_4$, $\nu_3$</td>
<td>0.078, 0.159</td>
<td>0.078, 0.159</td>
</tr>
<tr>
<td>Indirect vibrational excitation</td>
<td>4.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Electron attachment</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Electronic excitation (dissociation into neutral fragments)$^+$</td>
<td>12.5 (10)</td>
<td>12.5 (10)</td>
</tr>
<tr>
<td>Dissociative ionization$^+$</td>
<td>15.9</td>
<td>15.9</td>
</tr>
</tbody>
</table>

$^+$All electronic excited states of CF$_4$ and CF$_4^+$ ($\tau < 10$ $\mu$s) seem to dissociate or predissociate.

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Dissociation into neutral fragments in CF$_4$

\[ \text{e}^- + \text{CF}_4 \rightarrow \text{CF}_3 + \text{F} + \text{e}^- \]

Energy threshold: \(10 - 12.5\) eV (？)

Dissociation energy: \(D(\text{CF}_3 - \text{F}) = 5.25\) eV

Electronic excited states of CF$_3^*$:

\[1E' (7.95\) eV), 2A_2'' (7.68 \) eV), 2A_1' (8.40 \) eV).\]

Observed electronic transitions:

\[\text{CF}_3^* (1E',2A_2'' \rightarrow 1A_1' (repulsive state)) \text{ visible } \sim 620 \) nm\]

\[\text{CF}_3^* (2A_1' \rightarrow 1A_2'' (ground state)) \text{ UV } \sim 265 \) nm\]

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Total cross section for dissociation of CF$_4$ into neutrals

Mean power lost in collisions in a He+40%CF₄ mixture. Penning ionization is not considered.

Calculations based on the numerical solution of Boltzmann equation for a uniform electric field configuration. The code used was developed by the group of P. Ségur, CPAT, Toulouse, France

Mean power lost in collisions in a Ar+40%CF₄ mixture.
Number of collisions per cm leading to dissociation of CF$_4$ into neutral fragments, as a function of the electric field.

Number of collisions per cm leading to excitation of Ar$^*$ (2p+high lying forbidden) levels, as a function of the electric field.

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Dissociative ionization of CF$_4$

### A) CF$_4$\(^{+*}\) dissociates before emitting:
- $D$(CF$_3$-F) = 5.25 eV
- IP (CF$_3$) = 9.25 eV
- CF$_3$\(^{+*}\) → CF$_3$\(^+\) + hv (UV)

### B) CF$_4$\(^{+*}\) emits before dissociating
- CF$_4$\(^{+*}\) (\(\tilde{\Gamma}\)) → CF$_4$\(^+\) (\(\tilde{X}\)) + hv(\(\sim 160\) nm)
- → CF$_4$\(^{+*}\) (\(\tilde{A}\)) + hv(\(\sim 240\) nm)
- → CF$_4$\(^{+*}\) (\(\tilde{B}\)) + hv(\(\sim 290\) nm)

Fig. 8. Proposed dipole induced breakdown scheme for the ionic photofragmentation of CF$_4$. See text for details.

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Excitation and de-excitation mechanisms

CF$_4^+$ \xrightarrow{\text{dissociation}} \text{CF}_4^* \xrightarrow{\text{CF}_4} \text{CF}_3 + \text{F}

Ar$^+$

Ar$^{**}$ \xrightarrow{\text{products}} X = \text{Ar, CF}_4, \text{H}_2\text{O}, ... 

Ar$^*$ (2p) \xrightarrow{\text{products}} \text{Ar} \xrightarrow{\text{products}} \text{CF}_4 (\nu') 

X = \text{Ar, CF}_4, \text{H}_2\text{O}, ...
Excitation and de-excitation mechanisms

CF₄

He

CF₃ + F

CF₄ (ν')

CF₄^+

CF₄

He^+

He**

He*

CF₄^+(*)

X = He, H₂O, ...

products

products
Ar-TEA

Absorption length versus wavelength

Emission spectrum ($\Delta\lambda = 4$ nm)

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Excitation and de-excitation mechanisms

\[ X = \text{TEA, Ar, H}_2\text{O, ...} \]

\[ \text{Ar}^* \quad (2p) \rightarrow \text{products} \]

\[ \text{Ar}^* \quad (3s) \rightarrow \text{products} \]

\[ \text{TEA}^+ \rightarrow \text{TEA}^* \rightarrow \text{UV} \]

\[ \text{TEA} \rightarrow \text{Ar} \rightarrow \text{VUV} \]

\[ \text{Ar}^+ \]
Total light yields (PMT)

TEA mixtures: $\sigma_{\text{syst}} < 25\%$ ; $\text{He}/\text{CF}_4$ - 0.1-0.3 ph/e$^-$

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Nº of photons ($\lambda > 400$ nm) emitted per secondary electron as a function of the effective gain in (a) He+20%CF$_4$ and He+40% CF$_4$; (b) Ar+10%CF$_4$
Pulse height spectra from 5.9 keV X-rays

Ar+3%TEA
$V_{GEM} = 290$ V
$G_{eff} = 640$
($R = 53\%$ for $G = 460$)

Xe+3%TEA
$V_{GEM} = 320$ V
$G_{eff} = 370$

He+40%CF$_4$
$V_{GEM} = 460$ V
$G_{eff} = 320$

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Conclusions

• Ar-CF$_4$ mixtures emit mainly in the visible (CF$_3^*$) and in the NIR (Ar I 2p-3s atomic lines, which can be detected even for high CF$_4$ concentrations).

• He-CF$_4$ emit both in the UV and visible (CF$_3^*$)

• Visible emissions are more important in Ar/CF$_4$ than in He/CF$_4$.

• The GEM detector has been operated with Ar- and Xe-TEA mixtures but, for TEA concentrations above 5%, large leakage currents arise and the detector becomes unstable.

• No visible or NIR light was detected in Ar-TEA mixtures

• Light emitted in the gas (single GEM) was detected with a PMT operating in the pulse mode. The energy resolution is limited by statistics associated with charge multiplication process.