Fast component re-emission in Xe-doped liquid argon

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Outline:

• Liquid argon (LAr)
  • LAr scintillation
• Overview of previous studies
• Experimental setup
• Results
• Conclusion
Liquid argon

- Large scintillation yield ~40 photons/keVee
- Pulse Shape Discrimination (PSD) is possible
  - There are two scintillation components
    1. Singlet states ($^1\Sigma_u^+$) (~6 ns decay time)
    2. Triplet states ($^3\Sigma_u^+$) (~1.5 μs decay time)
  - Singlet/triplet ratio depends on the recoil type
- Problem: scintillation is in VUV light (~128 nm)
Problems of LAr scintillation registration

• Hard to detect LAr light ($\lambda = 128$ nm)
• Problems with reflectivity of detector walls
• Common solution is to use WLS
  - TPB
  - Another film WLS (?)
  - Xe doping ($\lambda = 175$ nm)

TPB problems:
1. Self-Light-Absorption
2. Covering problems
3. Degradation
4. Non-uniformity of covering
5. $4\pi$ re-emission

Xe-doping advantages:
1. Volume-distributed
2. Clean
3. No additional constructions inside the detector
4. No self-absorption
5. Re-emission in the point of interaction

Questions:
• Fast component reemission
• PSD efficiency
• Stability of mixture parameters
• Solubility problem

O. Cheshnovsky et al. Emission spectra of deep impurity states in solid and liquid rare gas alloys JCP (1972) 57

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## Previous studies (short list)

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Theor.</th>
<th>Slow</th>
<th>Fast</th>
<th>$\text{PSD}_{\text{low_ppm}}$</th>
<th>$\text{PSD}_{\text{high_ppm}}$</th>
<th>IR</th>
<th>Long run</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[2]</td>
<td>✓</td>
<td>✓</td>
<td>±</td>
<td>-</td>
<td>+ (?)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[3]</td>
<td>✓</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>+ (?)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[4]</td>
<td>✓</td>
<td>X</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>✓ (***)</td>
</tr>
<tr>
<td>[5],[6]</td>
<td>X</td>
<td>✓</td>
<td>+</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

(*) $\text{Ar}_2^* + \text{Xe} + \text{migration} \rightarrow (\text{ArXe})^* + \text{Ar}$  
( ArXe$^*$ + Xe + migration $\rightarrow$ Xe$^*_2 +$ Ar)  
(1) $I = A_f e^{-\frac{t}{t_f}} + A_s e^{-\frac{t}{t_s}} - A_d e^{-\frac{t}{t_d}}$

(**) $\text{IR} = \frac{1}{2} A f^2 + \frac{1}{2} A s^2 - A d^2$

(1) Shown in Summer 2018

2. C. G. Wahl et al *Pulse-shape discrimination and energy resolution of a liquid-argon scintillator with xenon doping* JINST (2014) 9
6. A. Buzulutskov *Photon emission and atomic collision processes in two-phase argon doped with xenon and nitrogen* EPL (2017) 117

Hot topic!
FEU-181 is VUV sensitive: MgF$_2$ window
Multalkaly photocathod
Can operate at cold (LN$_2$ temperatures)
## Runs:

<table>
<thead>
<tr>
<th>n, ppm (g/g)</th>
<th>insert</th>
<th>Direct</th>
<th>FS</th>
<th>TPB</th>
<th>Long run (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Teflon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 ÷ 300*</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓ (different)</td>
</tr>
<tr>
<td>300 ÷ 3000**</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓ (the best)</td>
</tr>
</tbody>
</table>


No fast component reemission with small concentration of Xe-doping

### Analysis:

- Averaged waveform (wf) from α-source events
- PSD (F40 = an area in first 40 ns of signal to the total area)
- Spectrum

~260 ppm Xe (g/g)
PSD and averaged WF

There is no WLS in the test chamber except of Xe in these runs. The FS filter is used to cut off direct LAr 128 nm light.

~0 ppm

250 ± 30 ppm

590 ± 75 ppm

1170 ± 120 ppm

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PSD-quality

• Two quality parameters:
  • $Q_{PSD}$
    • $\alpha$-events – events of interest
    • F40 cut: suppression of $\gamma$-background in a factor of 1000
  • $Q_{PSD}$ = percentage of remained $\alpha$-events
  • $d$
    • $d = \frac{\mu_\alpha - \mu_\gamma}{\sqrt{\sigma_\alpha^2 + \sigma_\gamma^2}}$, where $\mu$ – the mean of the Gaussian and $\sigma$ – RMS
  • Saturation at $\sim 2000$ ppm
Light yield (LY) parameters

- $\alpha$-peak parameters
- With increasing of Xe concentration:
  - LY increasing
  - Resolution becomes slightly better
- In tests with the FS filter (red triangles) LY parameters are better than for the tests with TPB (green circles)
- Saturation at the level of $\sim$2000 ppm
Stability of mixture

- Long-term run was performed for ~3000 ppm Xe mixture
- Simple one-exponential fit of the averaged wf in appropriate region gave $T_{seff}$ and $T_{feff}$ parameters
- Mean value of $\alpha$-peak in F40 distribution gives another parameter to check mixture stability
- Stability of all parameters related with Xe concentration:
  - $T_{seff}$
  - $T_{feff}$
  - F40

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Averaged WF analysis

- Fast component is becoming visible at ~600 ppm (g/g)
- A. Hitachi [NIM (1993) 327]: transfer constant is in ~3 times larger for the fast component
- Model (1) [C. G. Wahl et al, JINST (2014) 9] should be extended for high Xe concentrations
- In this case light emission should be represented by 4 terms model (3)
- $T_{ds}$ – transfer time for the slow component, $T_{df}$ – transfer time for the fast component

- $T_f$, $T_s$, $T_{df}$ & $T_{ds}$ or $T_d$ are the fit parameters
- Unfortunately, errors are big
  - Electronics noise
  - Trigger effect
  - Averaging procedure
  - etc

\[ (1) I = A_f e^{-\frac{t}{T_f}} + A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}} \]
\[ (2) I = A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}} \]
\[ (3) I = A_f e^{-\frac{t}{T_f}} + A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}} - A_d e^{-\frac{t}{T_{ds}}} \]
Fit parameters

- Fast and slow component decay time are in agreement with previous studies.
- Introducing the 4th term into the light emission model allows $T_{ds}$ to follow power law behavior.
- First experimental measurement of transfer rate constant for the fast component

$$k(1\Sigma_u^+) = \frac{1}{T_d \cdot [M]} = 0.9^{+2.3}_{-0.3} \cdot 10^{-11} cm^3/s$$
- Theoretical prediction: $k(1\Sigma_u^+) = 3.3 \cdot 10^{-11} cm^3/s$
For further investigations

- $T_{df}$ appear to be higher than expected (~7ns)
- It is comparable to the fast component decay time
- There should be a fraction of direct LAr scintillation (128 nm)
- At the same time, transfer process saturated at this level of Xe concentration
- Two runs with high Xe concentration were performed
  - With TPB (red line)
  - Direct light detection (black line)
- Averaged WFs have different shape than expected
- VUV light in the slow component from (ArXe)* molecules?
  - Previous spectrometric studies claim that it is possible but it is not clear will it vanish at high Xe concentration or not

- Speculative but possible answer is the another transfer mechanism for the fast component
- E.g. direct excitation of Xe atoms by 128 nm photons

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Conclusion

- Both fast and slow component reemitted with high Xe concentration
- Observed (with increasing Xe concentration):
  - Increasing of LY and resolution improvement
  - Decreasing of the slow component decay time
  - Increasing of PSD efficiency
    - Which is related to the increasing of the fast component portion re-emission
  - Mixture is stable during the long run
- First experimental measurement of transfer constant for the fast component
- Xe-dopant as WLS looks promising for large-scale LAr detectors
- But:
  - Should be checked linearity with energy
  - PSD for different source types
  - Uniformity in large detector
  - Transfer mechanism is not clear

Thank you for your attention!
Backup
Test chamber: gas system

1 – vacuum vessel; 2 – PMT; 3 – Copper housing with a wire heater attached; 4 – inner volume, 5 – LN₂ bath; 6 – heater and thermocontrol; 7 – gas filter Mycrolys; 8 – electromagnetic pump “Nord” & RGA; 9 – Ar (99,9995%); 10 – cryogenic pumps; B1– B3 – vacuometer; M1 – M3 – manometers; V1– V15 – valves.
Previous studies

- S. Kubota [1]: Ar*(Σ3*) transfer energy to Xe:
  - Ar2* + Xe + migration → (ArXe)* + Ar
  - (ArXe)* + Xe + migration → Xe2* + Ar

- D.N. McKinsey et al [2]: Added singlet states to the model

- Light emission [2]:

\[
I = A_f e^{-\frac{t}{T_f}} + A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}}
\]

(1)

- Only the small part of singlets reemitted by Xe

Approximation with the model (1).


Previous studies

• D.N. McKinsey et al [2]:
  • Statistic is low => only hint
  • Very complicated scheme of Xe introducing and measurements
  • TPB
  • PSD is bad with low Xe conc.
  • PSD become better then in pure LAr with high dopands
  • They don’t know the reason of PSD improvement
  • $T_d$ is lower for 1000 ppm than it should be according their model

• P. Peiffer et al [3]:
  • TPB in all measurements
  • PSD improved with Xe conc of 300 ppm
  • Don’t know the reason

• Neumeier et al [4]:
  • Solubility problem: 30 ppm is a limit
  • Transfer is ended at 10 ppm (by mole)
  • Electrons (!)


Previous studies

• A. Buzulutskov [5]:

\[
(17) \quad \text{Ar}_2(1,3\Sigma_u^+) + \text{Xe} \rightarrow \quad k_{17}(3\Sigma_u^+) \sim 87 \text{ K} \quad [17-19] \quad \sim 5.3 \text{ ns}
\]

\[
2\text{Ar} + \text{Xe}^+(n = 1, 2, 2P_{3/2}) \quad (0.8 - 1) \times 10^{-11} \text{ cm}^3\text{s}^{-1}
\]

\[
\tau_{17}(3\Sigma_u^+) < 90 \text{ ns} \quad 87 \text{ K} \quad [18,20] \quad < 90 \text{ ns}
\]

\[
k_{17}(1\Sigma_u^+) \sim 3.3 \times 10^{-11} \text{ cm}^3\text{s}^{-1} \quad 87 \text{ K} \quad [19] \quad \sim 1.4 \text{ ns}
\]

For the singlet state, higher concentration of dopants is needed for collisional processes to occur because of its short lifetime. Since \( \rho \propto C^{1/4} \propto (1/\tau_0)^{1/4} \), we have \( \rho = 1.4 \times (1.6 \mu\text{s}/7 \text{ ns})^{1/4} \approx 5.4 \text{ Å} \) for \( \text{Ar}_2^+ (1\Sigma_u^+) - \text{Xe} \) assuming the same overlap integrals as the triplet state. Then we have \( k_{1,4} \approx 3.3 \times 10^{-11} \text{ cm}^3/\text{s} \). It is necessary for \( [\text{Xe}] \approx 200 \text{ ppm} \) to

• A. Hitachi [6]:


Why F40?

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Data analysis

Wf of one event in Xe dopant test

Signal start

Averaged WF for pure LAr, direct light detection

Pulses positions

Number of pulses

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Coincidence scheme

Under the test chamber

Background

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A. Buzulutskov Photon emission and atomic collision processes in two-phase argon doped with xenon and nitrogen EPL (2017) 117
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