Fast component re-emission in Xe-doped liquid argon

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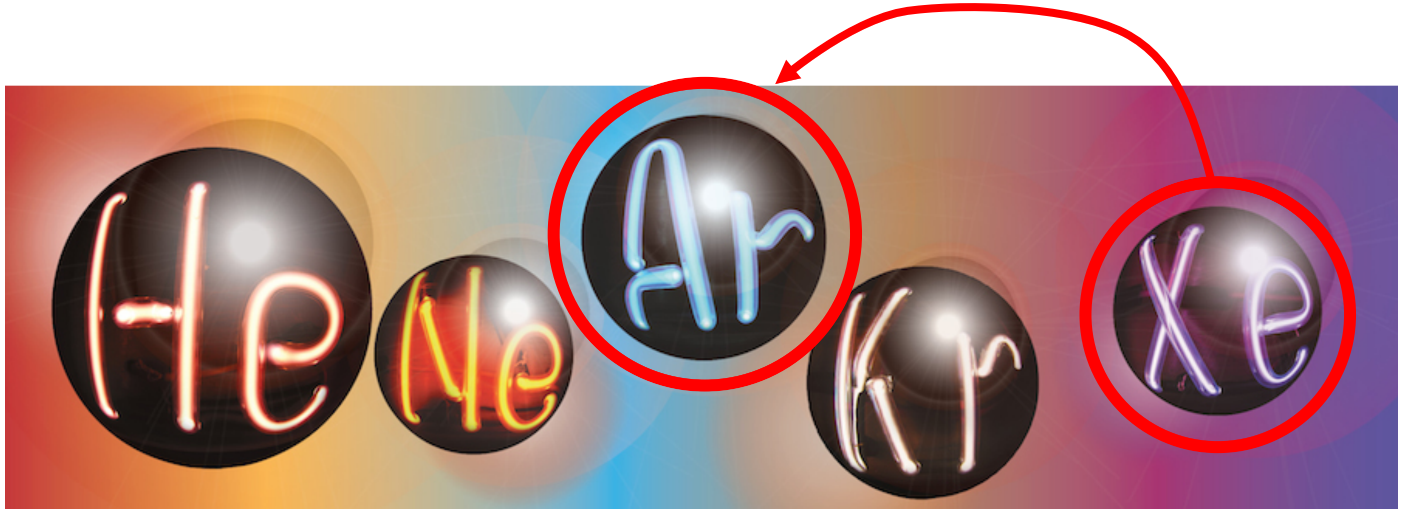
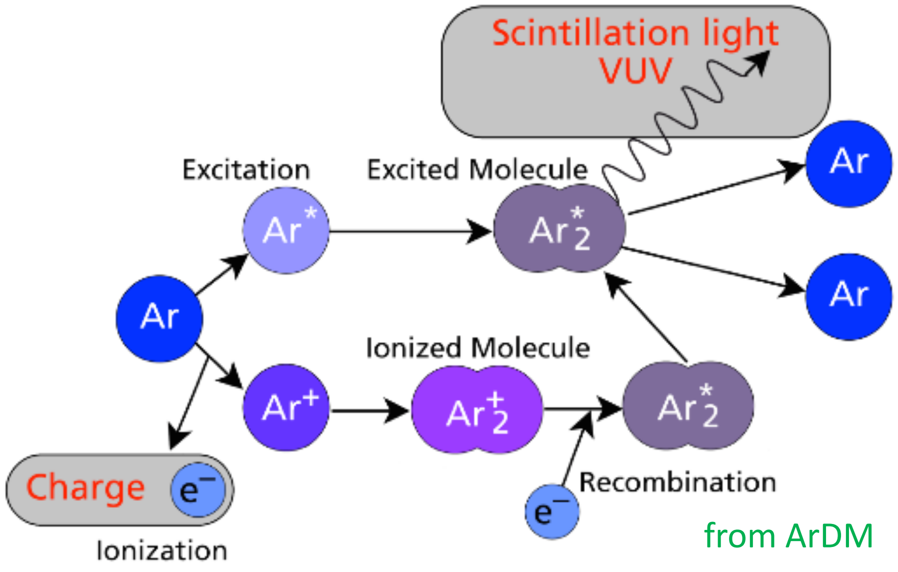
Outline:

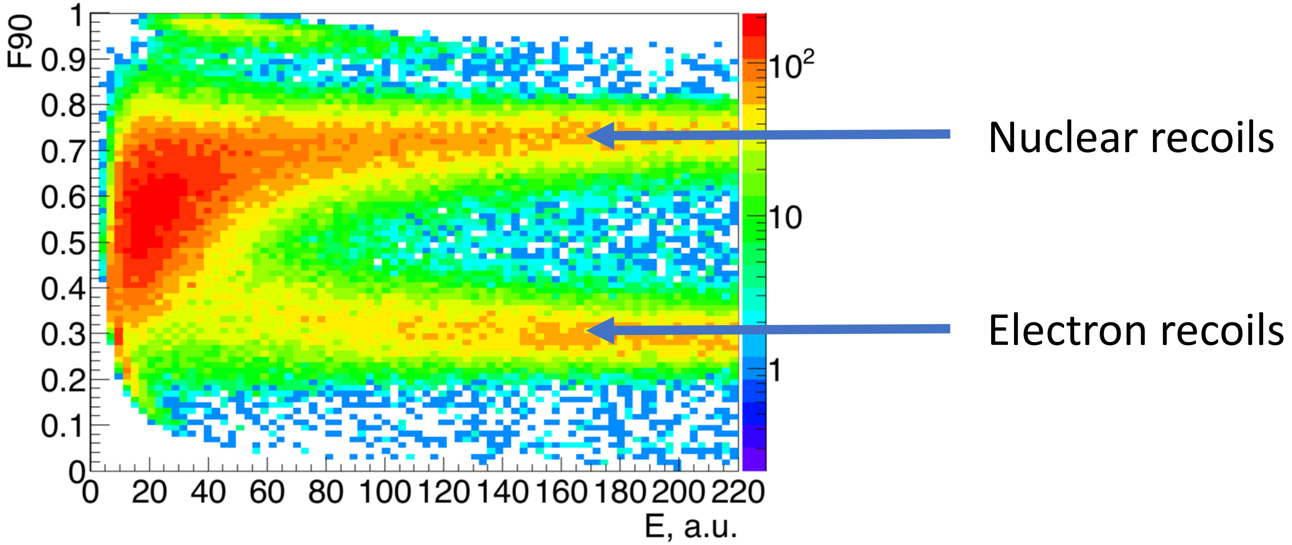
- Liquid argon (LAr)
  - LAr scintillation
- Overview of previous studies
- Experimental setup
- Results
- Conclusion



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)

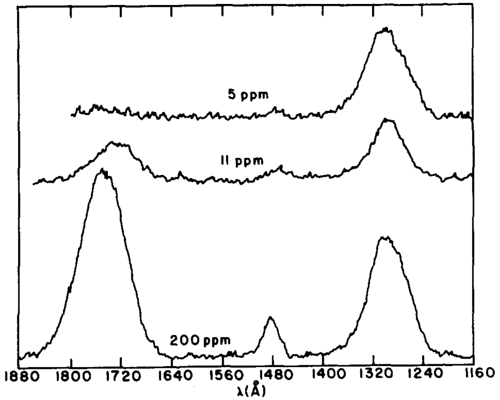




Problems of LAr scintillation registration

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

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



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

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

Previous studies (short list)

	Exp.	Theor.	Slow	Fast	PSD_{low_ppm}	PSD_{high_ppm}	IR	Long run
[1]	✓	✓(*)	+	–	✗	✗	✗	✗
[2]	✓	✓(**)	+	±	–	+(?)	✗	✗
[3]	✓	✗	+	–	–	+(?)	✗	✗
[4]	✓	✗	+	–	–	✗	✓	✓(***)
[5],[6]	✗	✓	+	+	✗	✗	✗	✗

(*) $Ar_2^* + Xe + \text{migration} \rightarrow (ArXe)^* + Ar$

$(ArXe)^* + Xe + \text{migration} \rightarrow Xe_2^* + Ar$

(**) $$I = A_f e^{-\frac{t}{T_f}} + A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}} \quad (1)$$

(***) Shown in Summer 2018

[1] S. Kubota et al *The suppression of the slow component in xenon-doped liquid argon scintillation* NIM (1993) 327

[2] C. G. Wahl et al *Pulse-shape discrimination and energy resolution of a liquid-argon scintillator with xenon doping* JINST (2014) 9

[3] P. Peiffer et al *Pulse shape analysis of scintillation signals from pure and xenon-doped liquid argon for radioactive background identification* JINST (2008) 3

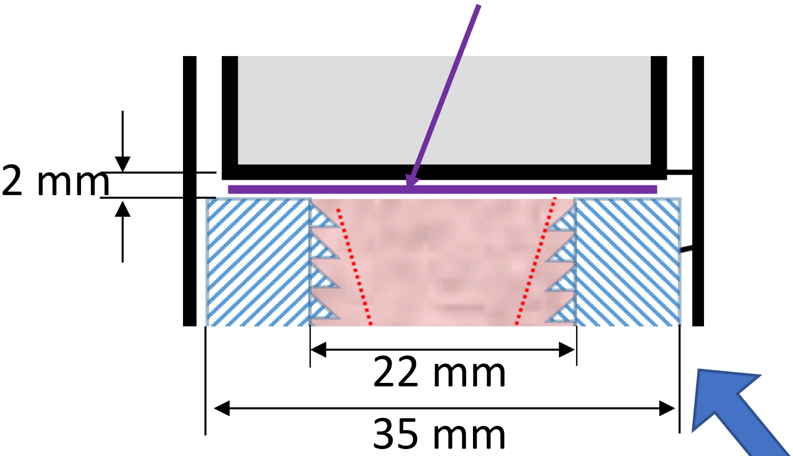
[4] A. Neumeir et al *Intense vacuum ultraviolet and infrared scintillation of liquid Ar-Xe mixtures* EPL (2015) 109

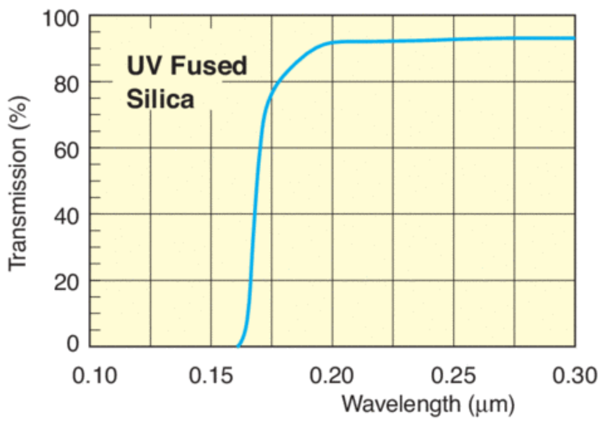
[5] A. Hitachi *Photon-mediated and collisional processes in liquid rare gases* NIM (1993) 327

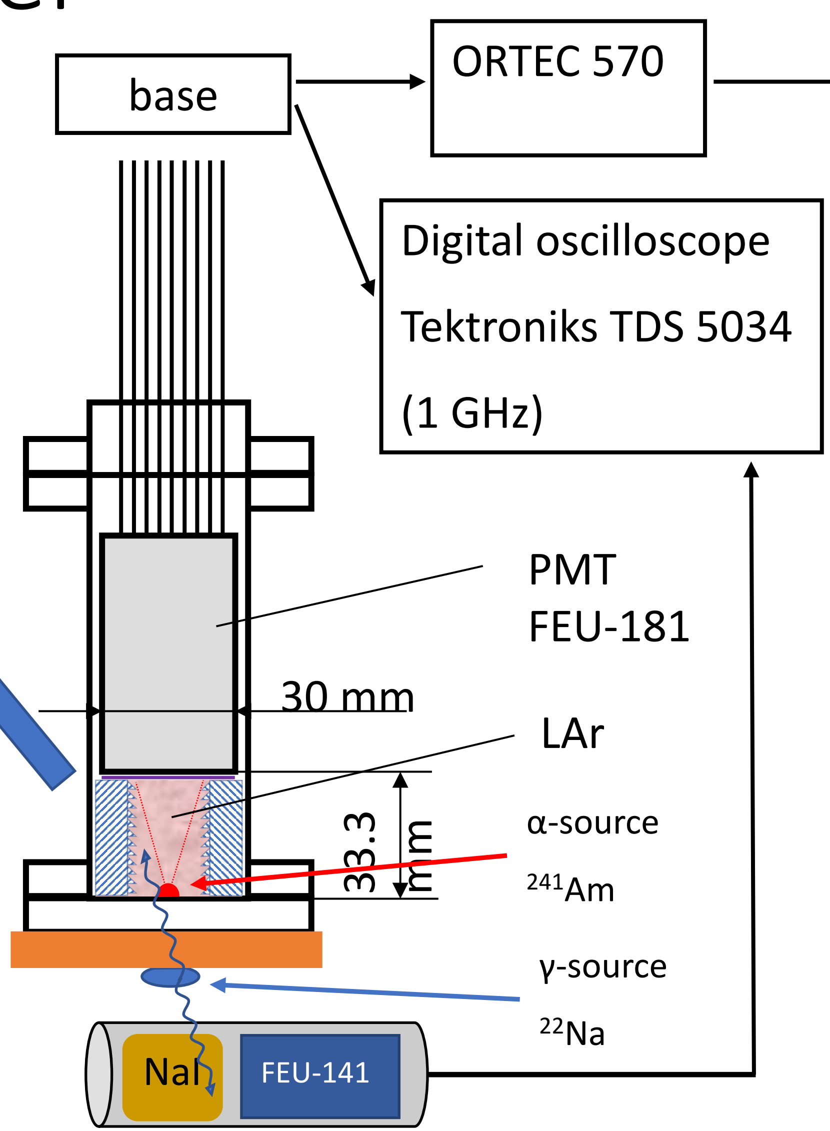
[6] A. Buzulutskov *Photon emission and atomic collision processes in two-phase argon doped with xenon and nitrogen* EPL (2017) 117

Hot topic!

Test chamber

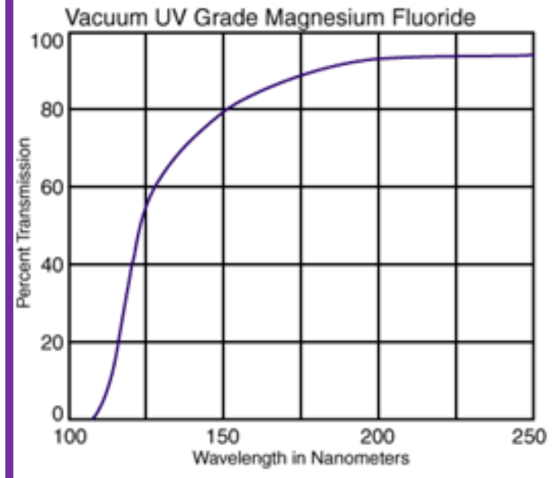






FEU-181 is VUV sensitive: MgF_2 window
Multialkaly photocathod

Can operate at cold (LN_2 temperatures)



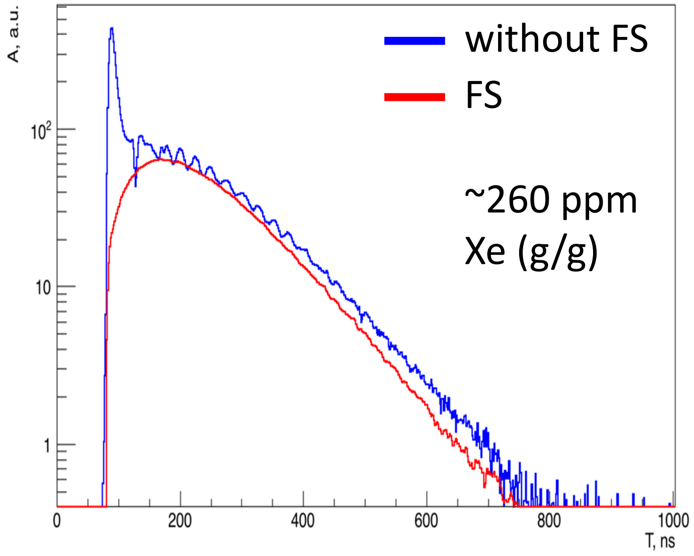
Runs:

n, ppm (g/g)	insert		Direct	FS	TPB	Long run (h)
	steel	Teflon				
0 ÷ 300*	✓	✓	✓	✓	✓(different)	31
300 ÷ 3000**	✗	✓	✓	✓	✓(the best)	54

* Akimov D et al, *Study of Xe-doping to LAr scintillator,* Journal of Physics: Conference Series (2017) 798

**** Akimov D et al, *Fast component re-emission in Xe-doped liquid argon,* [arXiv:1906.00836] → JINST**

No fast component reemission with small concentration of Xe-doping

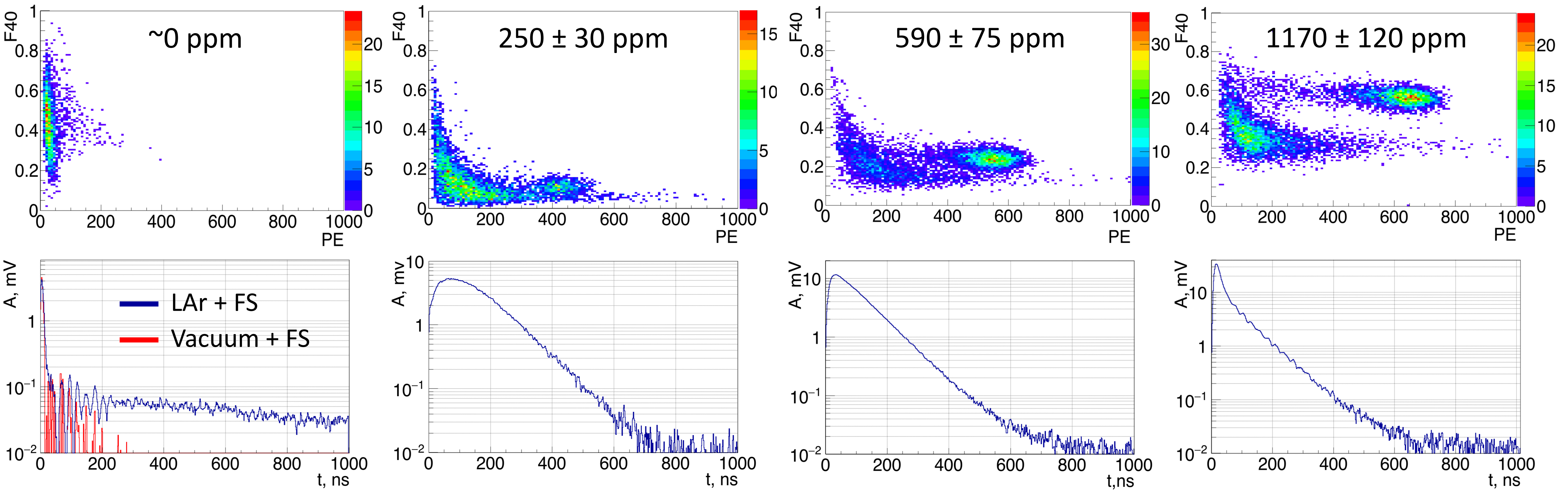


Analysis:

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

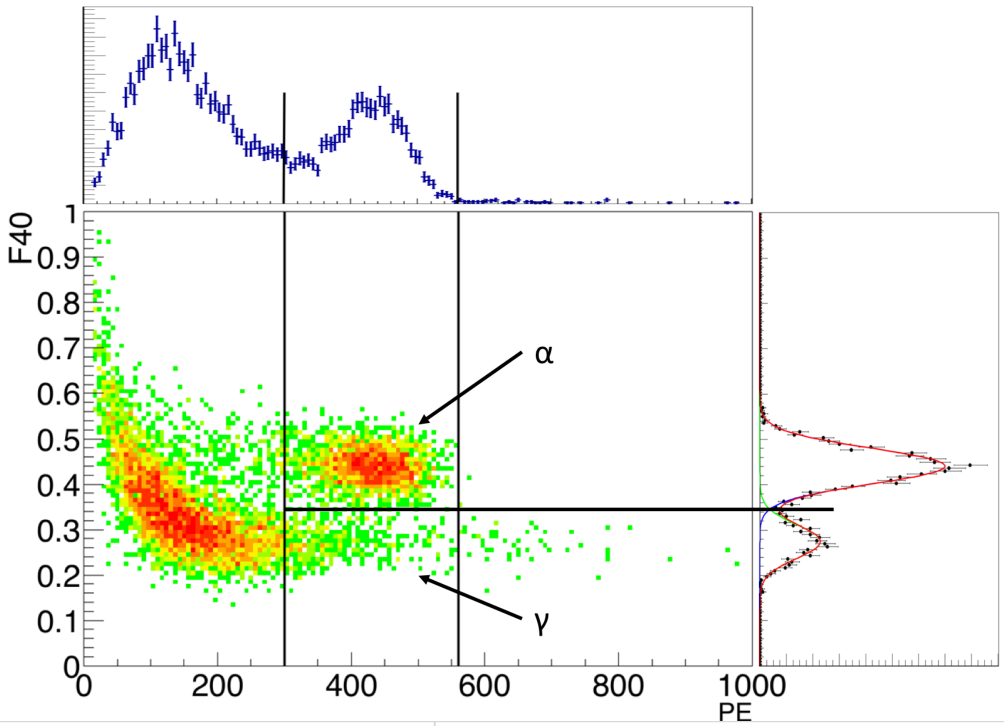
PSD and averaged WF

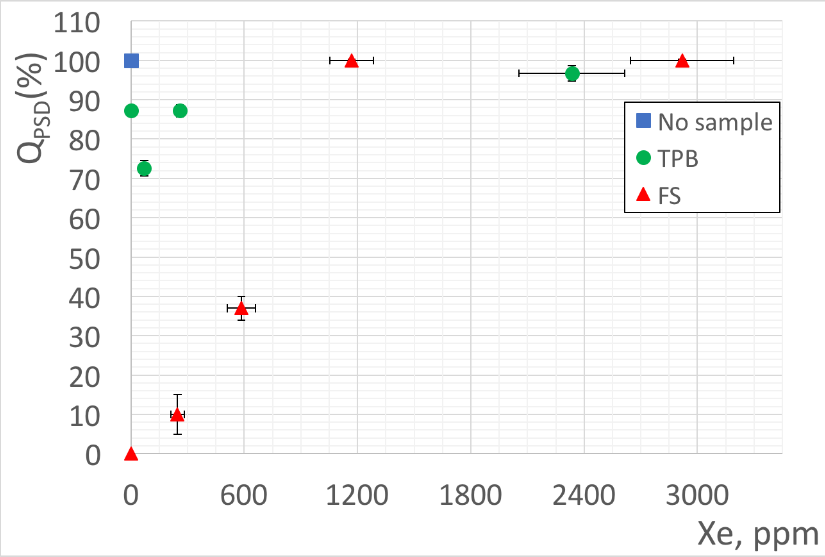
There is no WLS in the test chamber except of Xe in these runs.
The FS filter is used to cut off direct LAr 128 nm light.

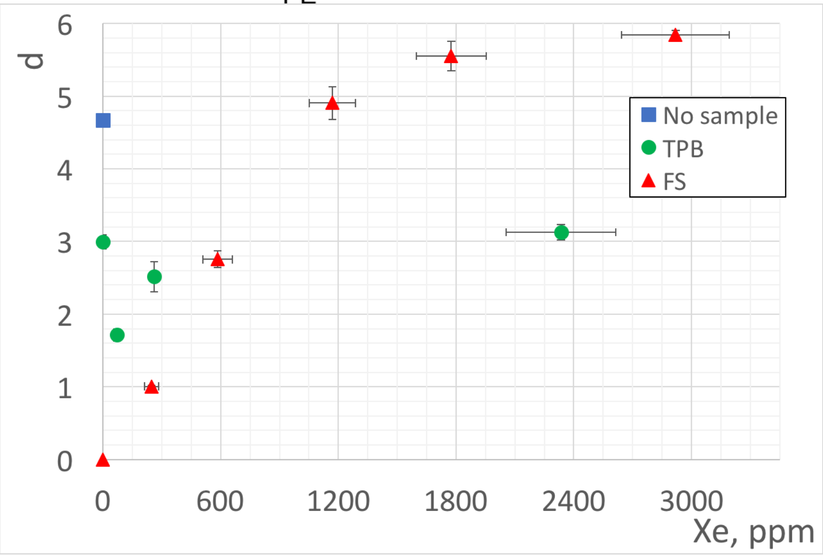


PSD-quality

- Two quality parameters:
- Q_{PSD}
  - α-events – events of interest
  - F40 cut: suppression of γ-background in a factor of 1000
  - Q_{PSD} = percentage of remained α-events
- d
  - $d = \frac{\mu_\alpha - \mu_\gamma}{\sqrt{\sigma_\alpha^2 + \sigma_\gamma^2}}$, where μ – the mean of the Gaussian and σ – RMS
- Saturation at ~2000 ppm

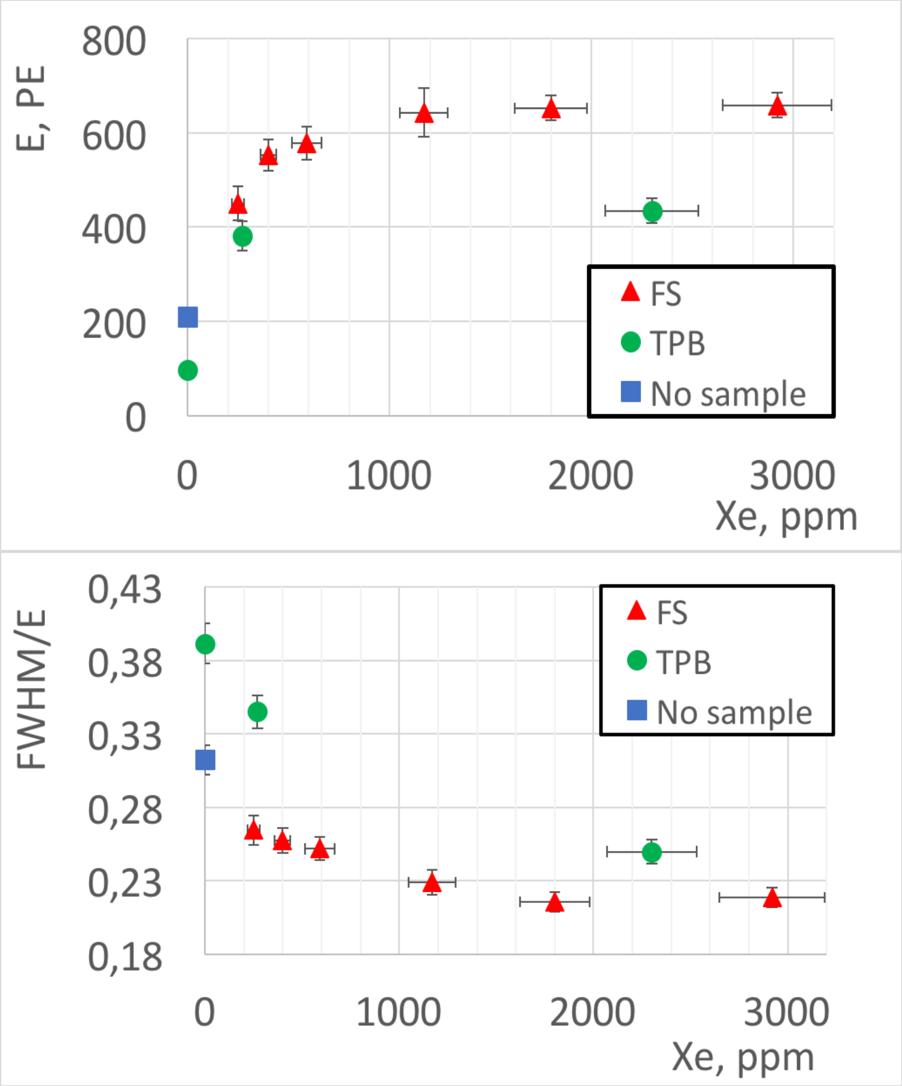






Light yield (LY) parameters

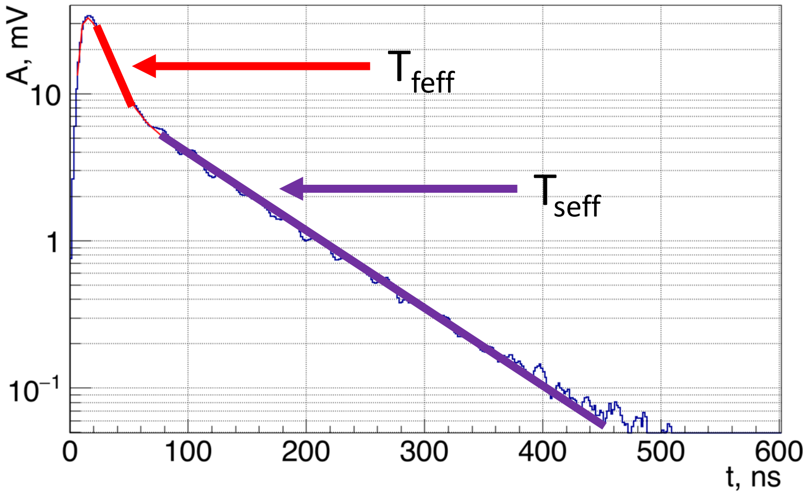
- α-peak parameters
- With increasing of Xe concentration:
  - LY increasing
  - Resolution becomes slightly better
- In tests with the FS filter (red triangles) LY parameters are better then for the tests with TPB (green circles)
- Saturation at the level of ~2000 ppm

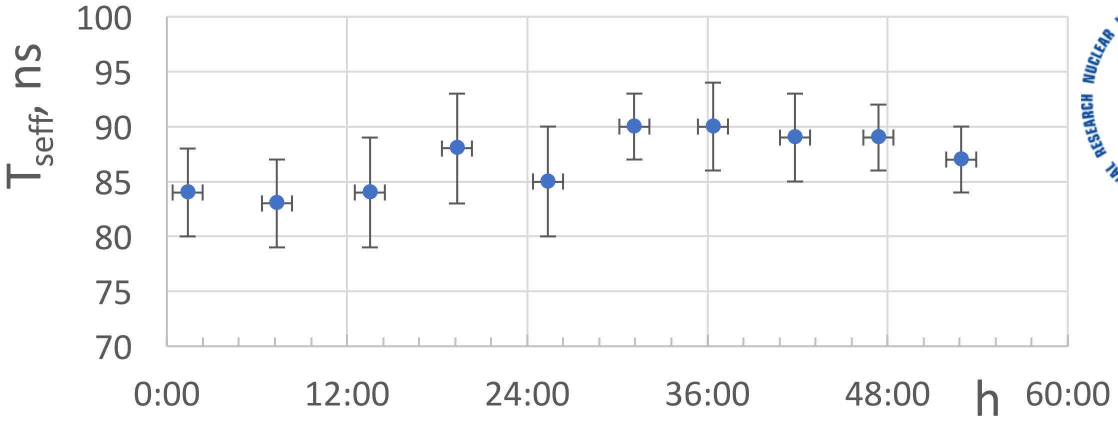


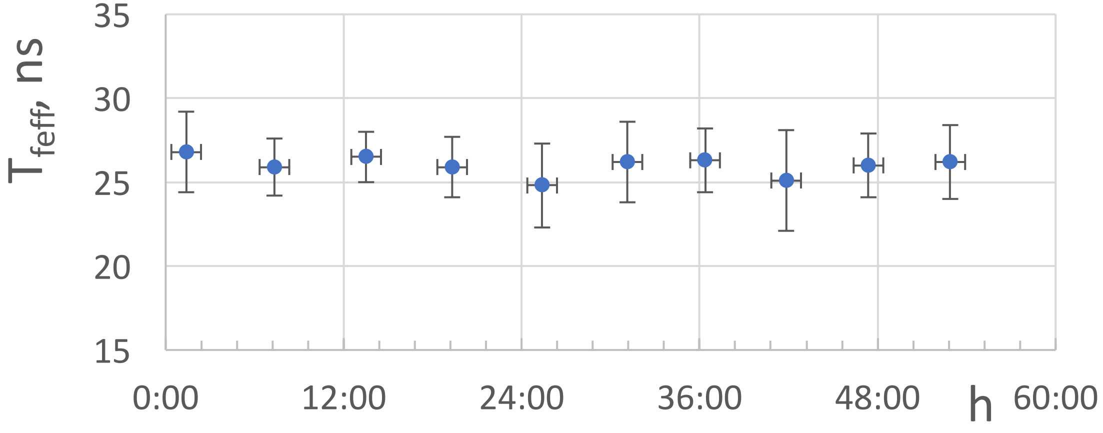
Stability of mixture

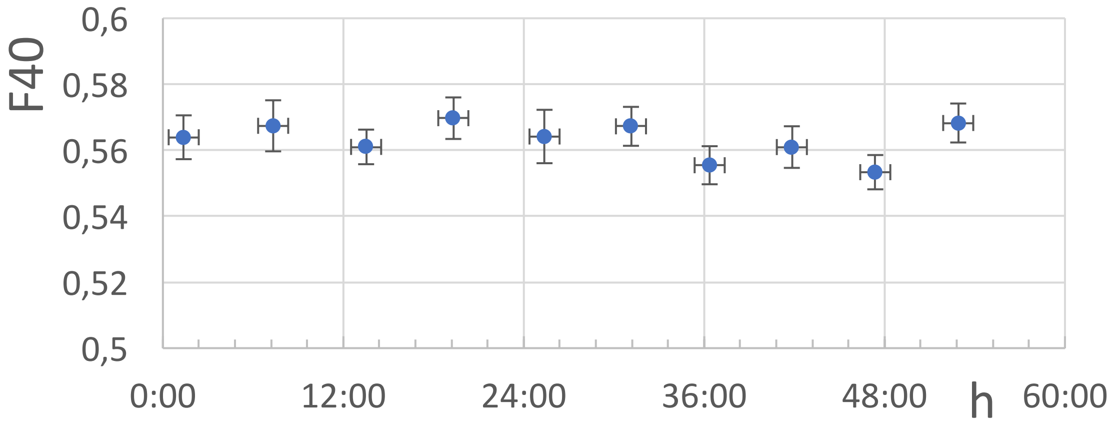
- Long-term run was performed for ~3000 ppm Xe mixture
- Simple one-exponental fit of the averaged wf in appropriate region gave T_{seff} and T_{feff} parameters
- Mean value of α-peak in F40 distribution gives another parameter to check mixture stability
- Stability of all parameters related with Xe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

Mixture is stable





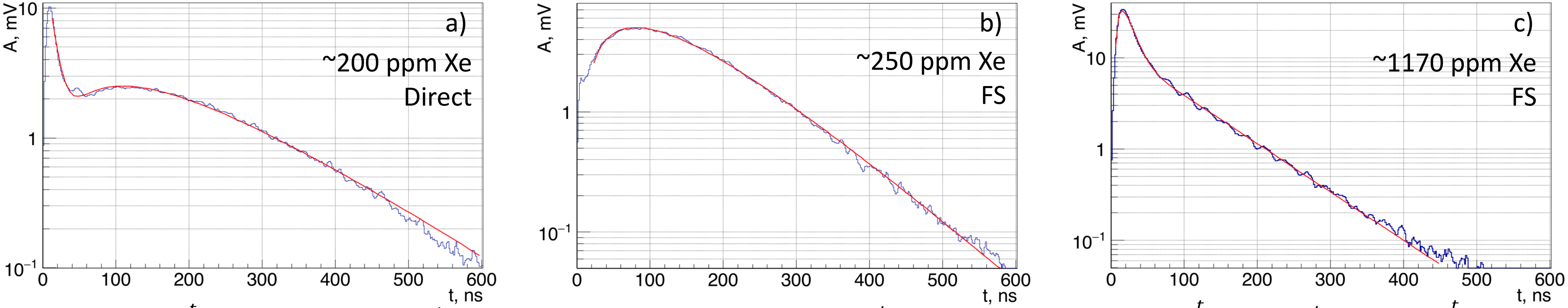




Averaged WF analysis

- 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



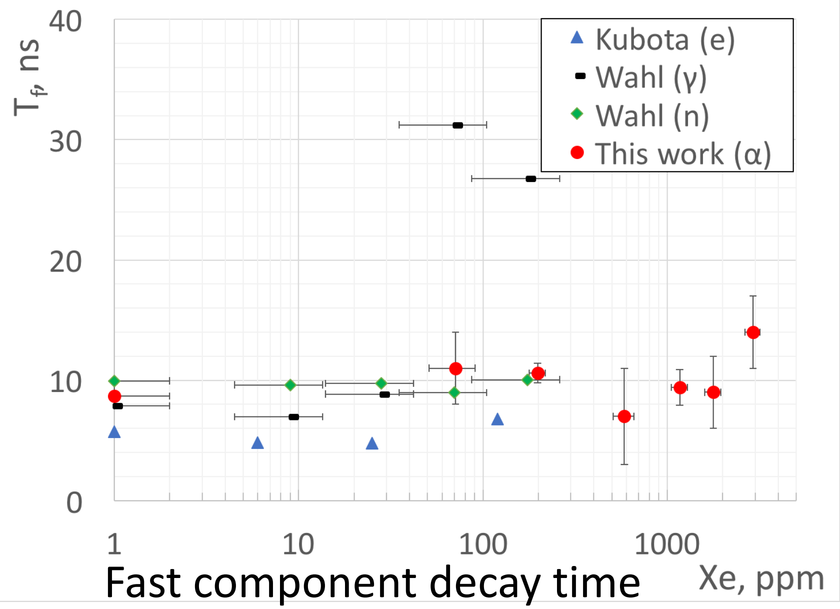
(1) $I = A_f e^{-\frac{t}{T_f}} + A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}}$

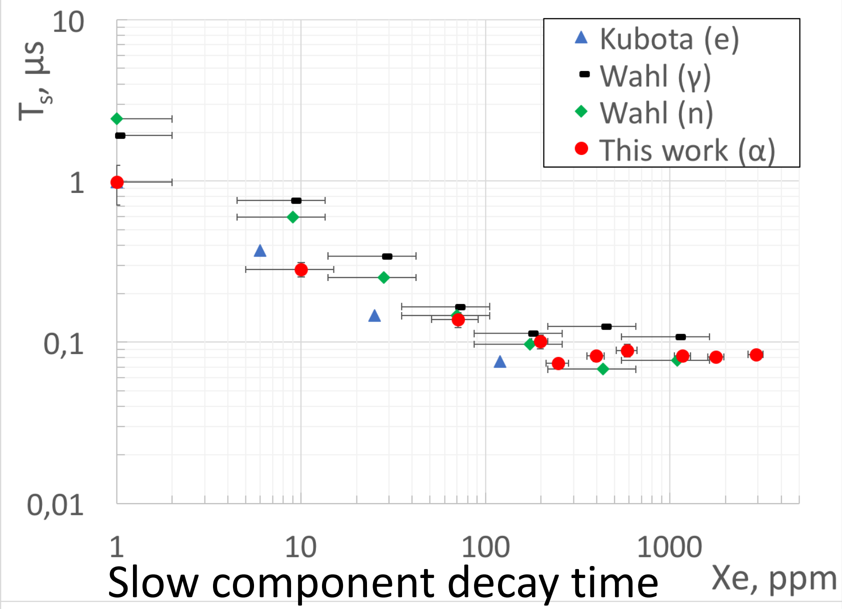
(2) $I = A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}}$

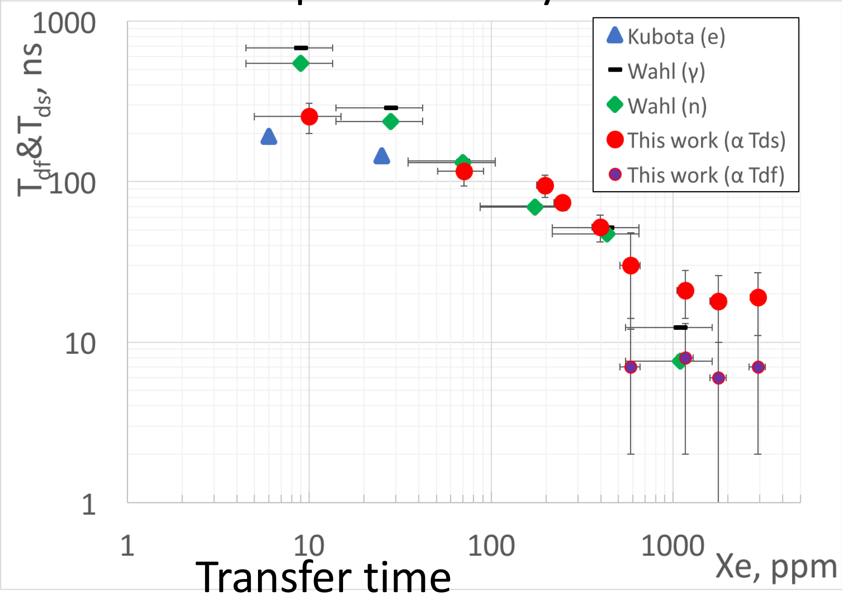
(3) $I = A_f e^{-\frac{t}{T_f}} + A_s e^{-\frac{t}{T_s}} - A_{df} e^{-\frac{t}{T_{df}}} - A_{ds} e^{-\frac{t}{T_{ds}}}$

Fit parameters

- Fast and slow component decay time are in agreement with previous studies







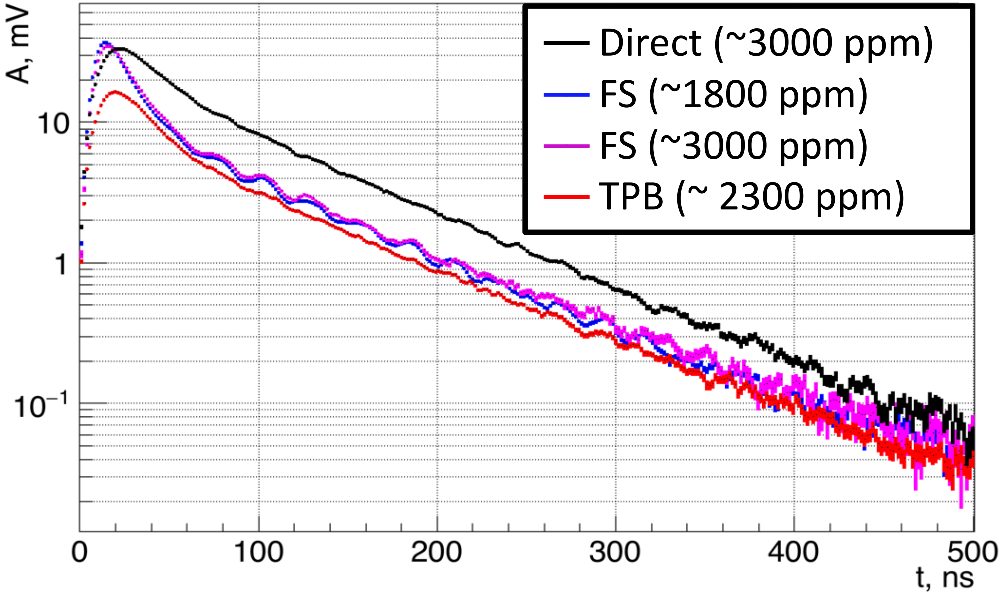
- Introducing the 4th term into the light emission model allows T_{ds} to follow power law behavior
- First experimental measurement of transfer rate constant for the fast component

$$k_{(^1\Sigma_u^+)} = \frac{1}{T_d \cdot [M]} = 0.9^{+2.3}_{-0.3} \cdot 10^{-11} cm^3/s$$

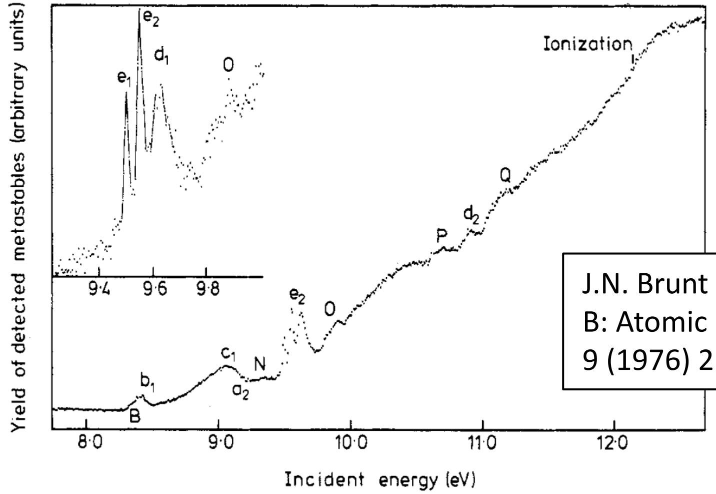
- Theoretical prediction: $k_{(^1\Sigma_u^+)} = 3.3 \cdot 10^{-11} cm^3/s$

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**



J.N. Brunt et al, Journal of Physics B: Atomic and Molecular Physics 9 (1976) 2195

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

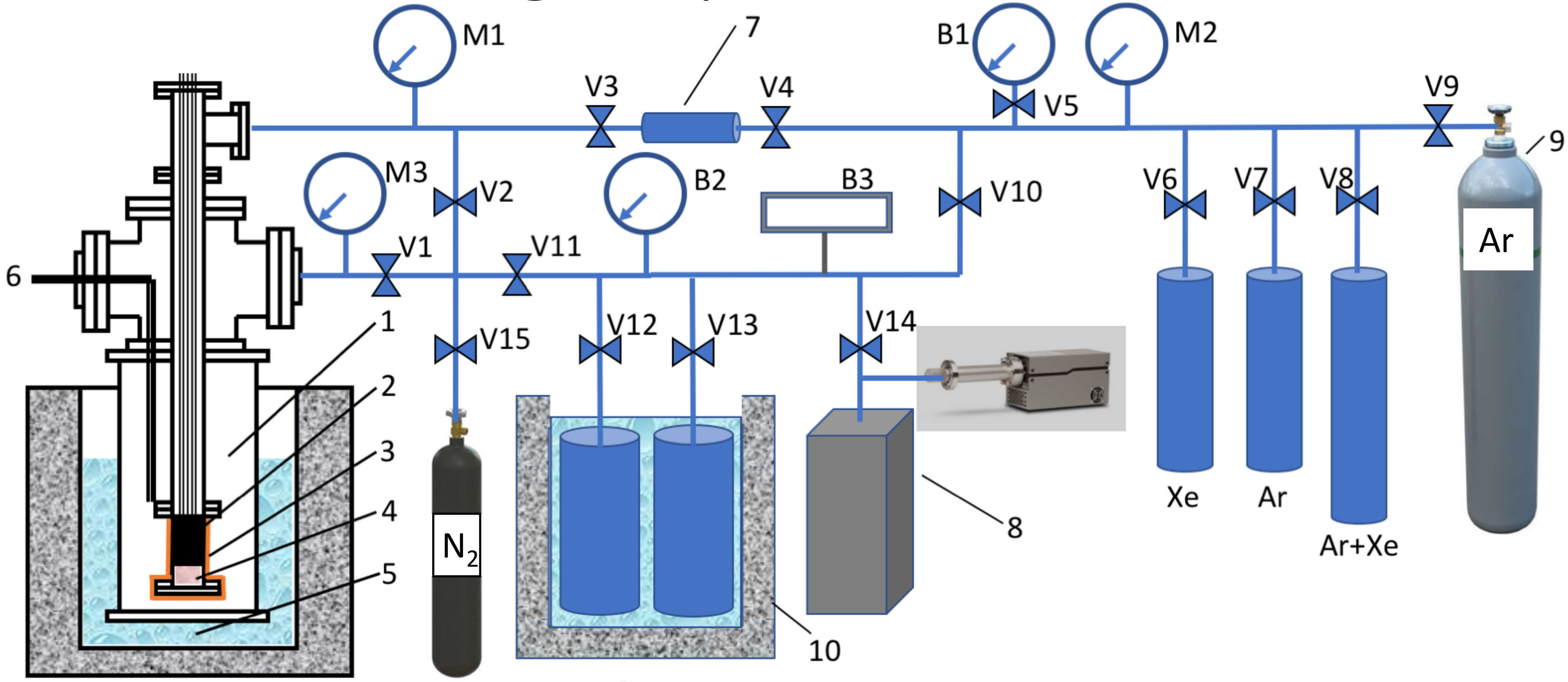
[arXiv:1906.00836]

- 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 – LN_2 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.

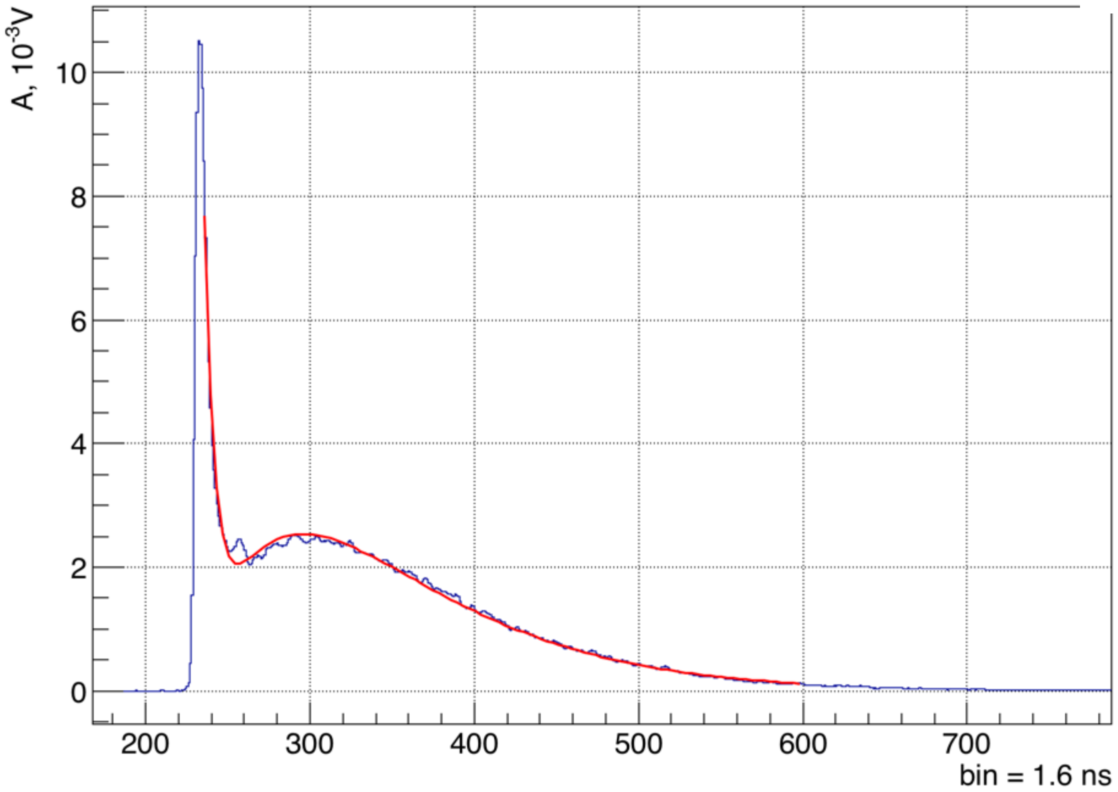
Previous studies

- S. Kubota [1]: $Ar^*(\Sigma_3^*)$ transfer energy to Xe:
  - Ar_2^* + Xe + migration → $(ArXe)^*$ + Ar
  - $(ArXe)^*$ + Xe + migration → Xe_2^* + Ar
- D.N. McKinsey et al [2]: Added singlet states to the model
- Light emission [2]:

$$I = A_f e^{-\frac{t}{T_f}} + A_s e^{-\frac{t}{T_s}} - A_d e^{-\frac{t}{T_d}} \quad (1)$$

T_f, T_s – fast and slow components decay times, T_d – time of energy transferring Ar* --> Xe

- Only the small part of singlets reemitted by Xe



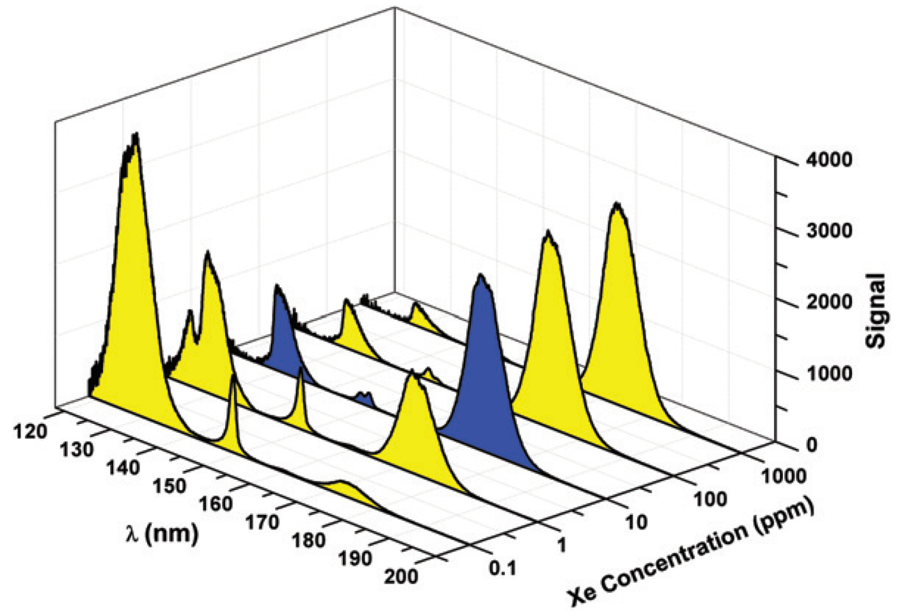
Approximation with the model (1).

[1] S. Kubota et al *The suppression of the slow component in xenon-doped liquid argon scintillation* NIM (1993) 327

[2] C. G. Wahl et al *Pulse-shape discrimination and energy resolution of a liquid-argon scintillator with xenon doping* JINST (2014) 9

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 (!)



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[4] A. Neumeir et al *Intense vacuum ultraviolet and infrared scintillation of liquid Ar-Xe mixtures* EPL (2015) 109

Previous studies

- A. Buzulutskov [5]:

(17) $Ar_2^*(^{1,3}\Sigma_u^+) + Xe \rightarrow$ $2Ar + Xe^*(n = 1, 2, {}^2P_{3/2})$	$k_{17}(^3\Sigma_u^+) \sim$ $(0.8 - 1) \times 10^{-11}$ cm^{3}s^{-1}	87 K	[17–19]	~5.3 ns
	$\tau_{17}(^3\Sigma_u^+) < 90$ ns	87 K	[18,20]	<90 ns
	$k_{17}(^1\Sigma_u^+) \sim 3.3 \times 10^{-11}$ cm^{3}s^{-1}	87 K	[19]	~1.4 ns

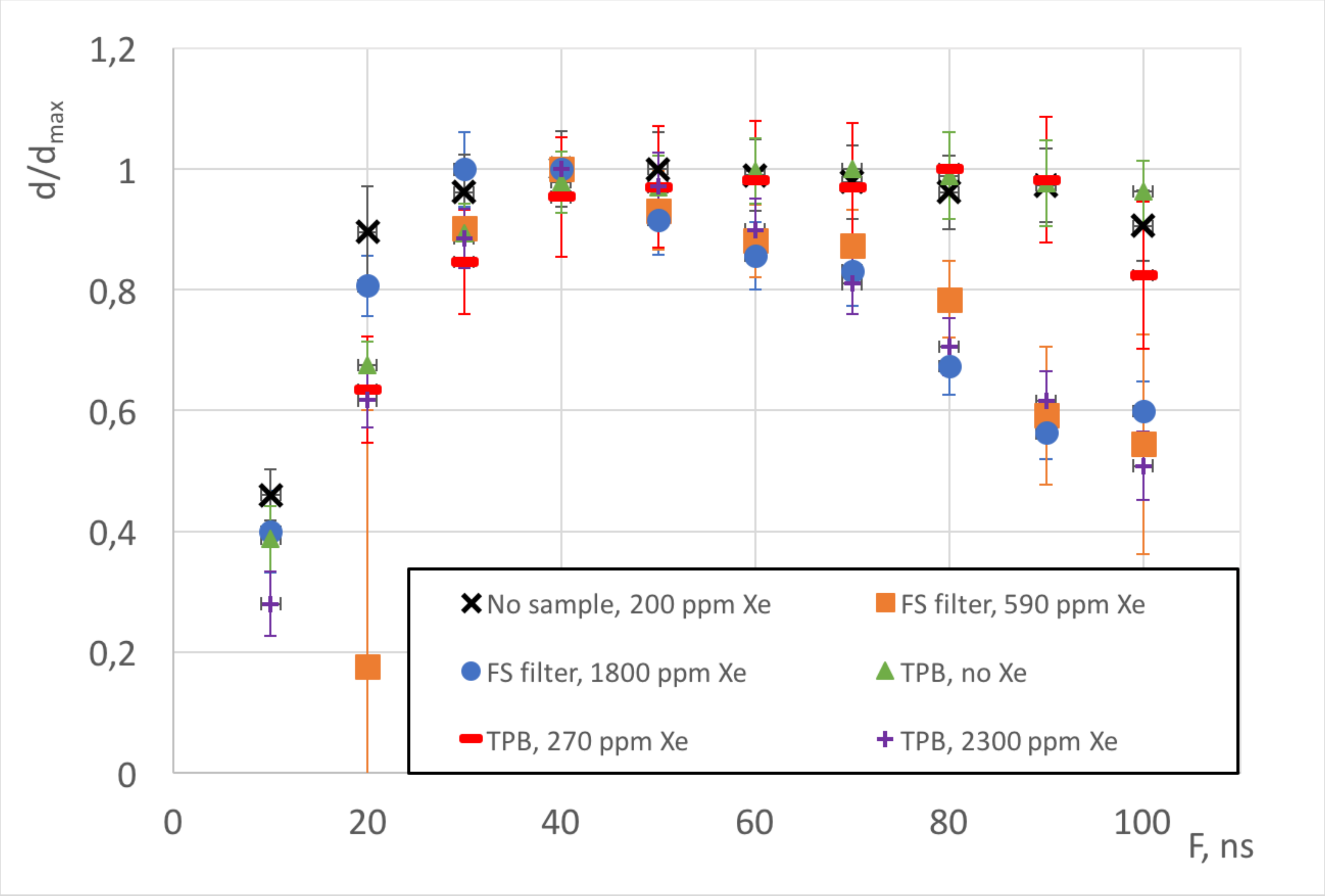
- A. Hitachi [6]:

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 $\rho = 1.4 \times (1.6\ \mu s/7\ ns)^{1/4} \approx 5.4$ Å for Ar_2^* $(^1\Sigma_u^+)$–Xe assuming the same overlap integrals as the triplet state. Then we have $k_{d-d} \approx 3.3 \times 10^{-11}$ cm^3/s. It is necessary for [Xe] ≈ 200 ppm to

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

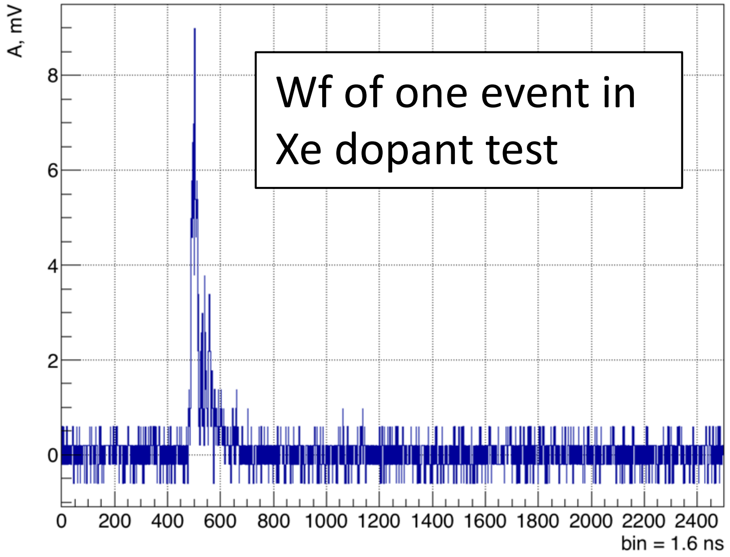
[6] A. Hitachi *Photon-mediated and collisional processes in liquid rare gases* NIM (1993) 327

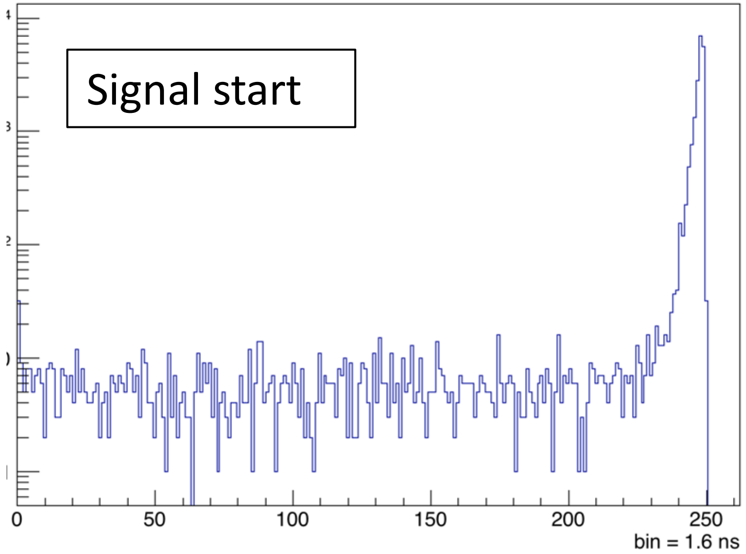
Why F40?

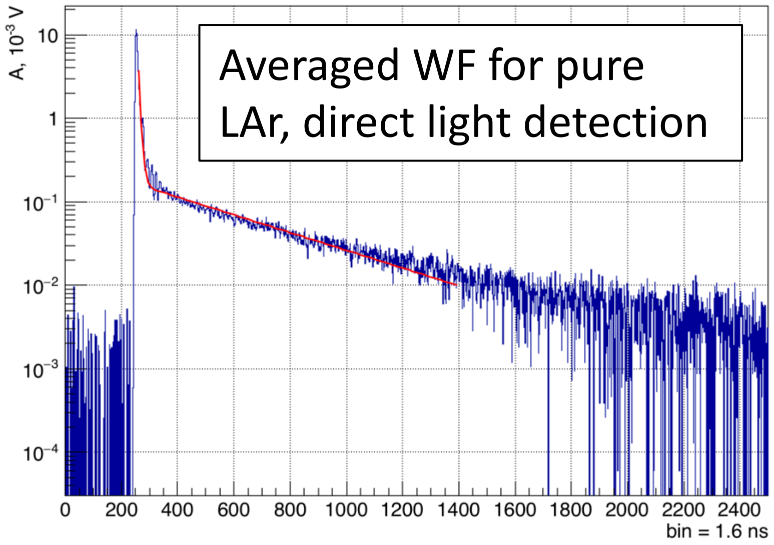


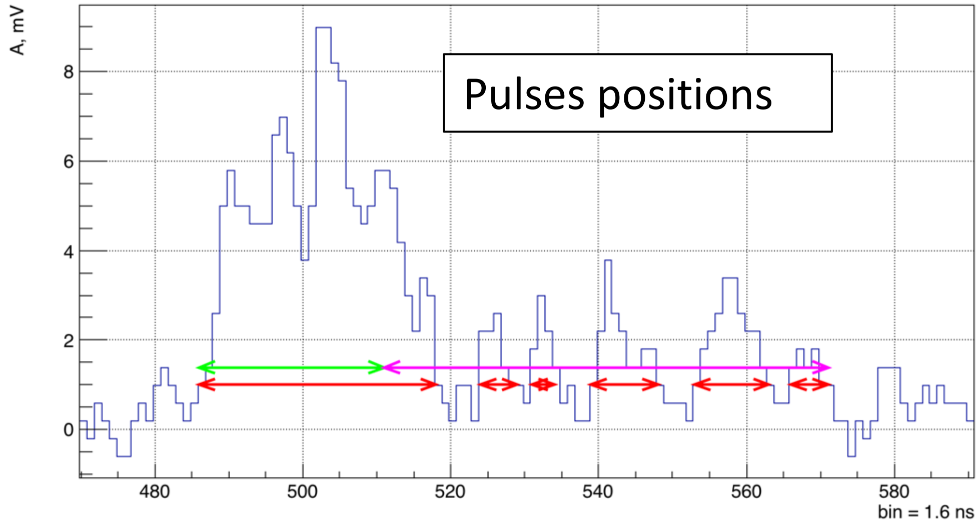
1,2
1
0,8
0,6
0,4
0,2
0
d/d_max
0
20
40
60
80
100
F, ns
No sample, 200 ppm Xe
FS filter, 590 ppm Xe
FS filter, 1800 ppm Xe
TPB, no Xe
TPB, 270 ppm Xe
TPB, 2300 ppm Xe

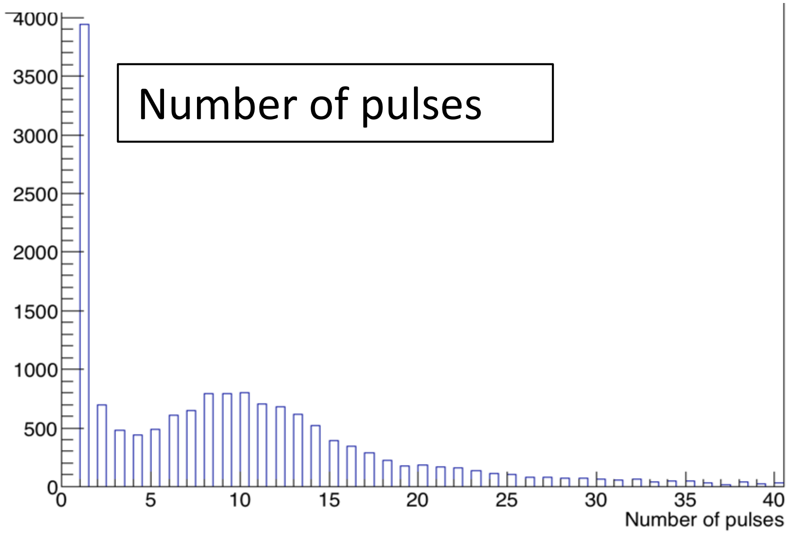
Data analysis



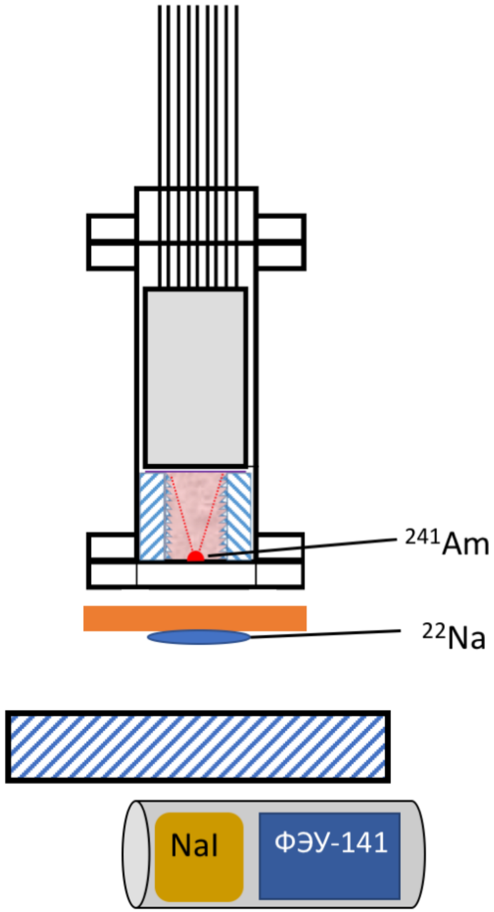


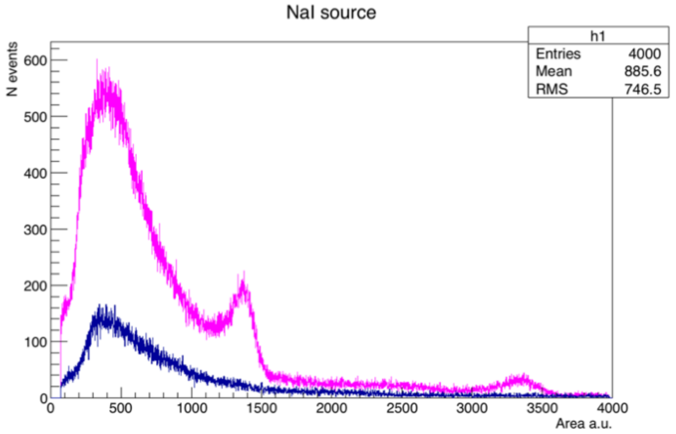






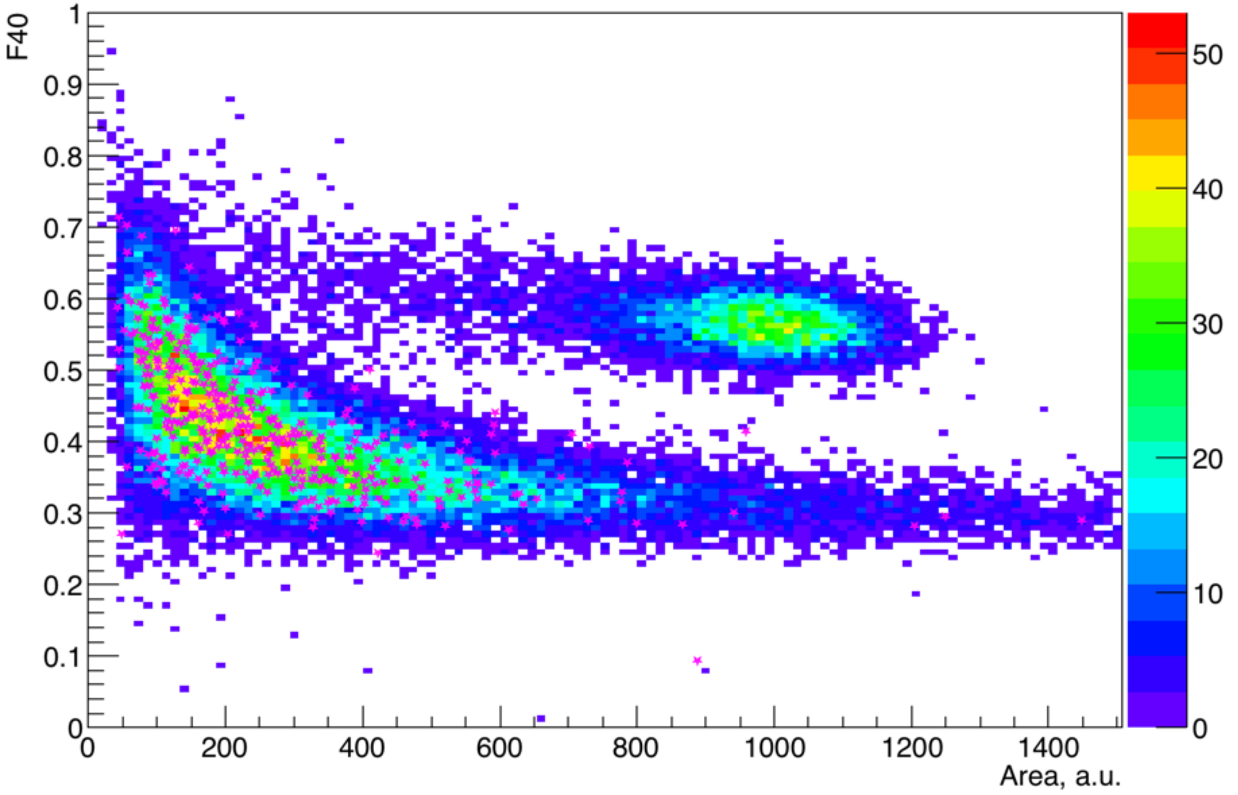
Coincidence scheme



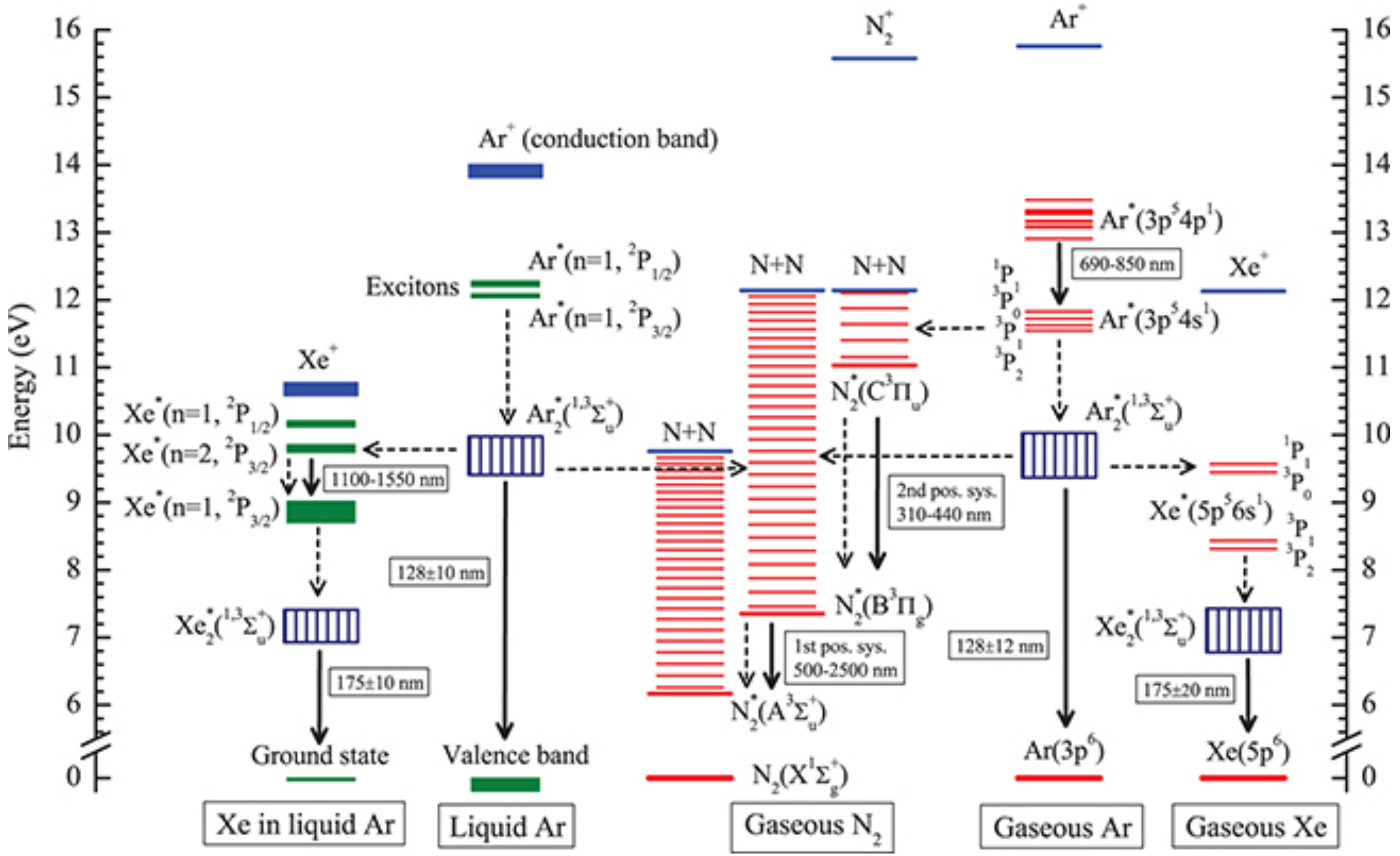


Under the test chamber

Background

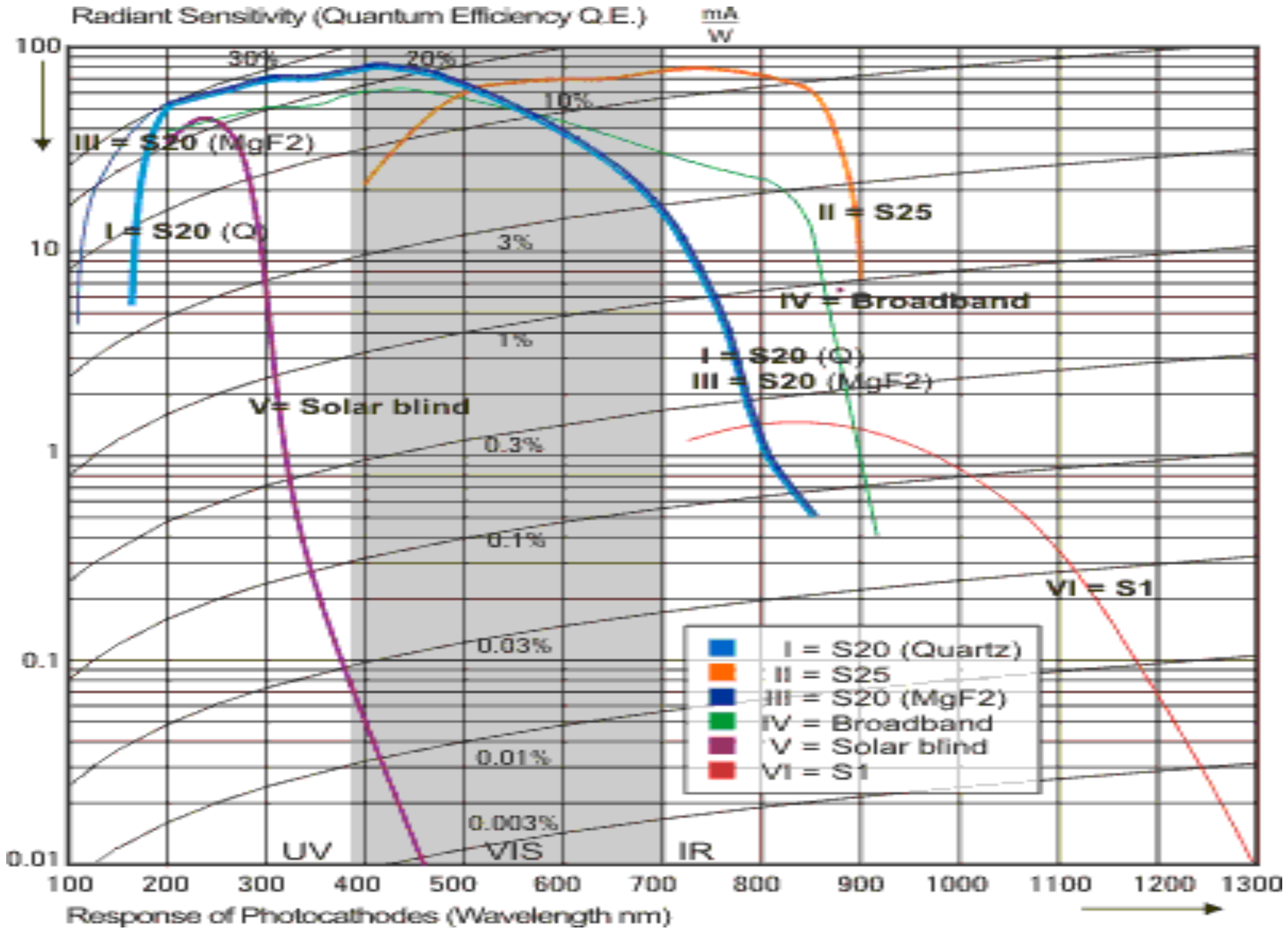


Energy levels scheme



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

PMT QE



Radiant Sensitivity (Quantum Efficiency Q.E.)
mA/W
100
10
1
0.1
0.01
30%
20%
10%
3%
1%
0.3%
0.1%
0.03%
0.01%
0.003%
III = S20 (MgF2)
I = S20 (Q)
II = S25
IV = Broadband
I = S20 (Q)
III = S20 (MgF2)
V= Solar blind
VI = S1
I = S20 (Quartz)
II = S25
III = S20 (MgF2)
IV = Broadband
V = Solar blind
VI = S1
UV
VIS
IR
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
Response of Photocathodes (Wavelength nm)