

Revealing neutral bremsstrahlung in two-phase argon electroluminescence

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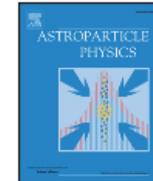
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Revealing neutral bremsstrahlung in two-phase argon electroluminescence



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[V. Oleynikov](#)^{a,b}, [L. Shekhtman](#)^{a,b}, [A. Sokolov](#)^{a,b}

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ABSTRACT

Proportional electroluminescence (EL) in noble gases has long been used in two-phase detectors for dark matter search, to record ionization signals induced by particle scattering in the noble-gas liquid (S2 signals). Until recently, it was believed that proportional electroluminescence was fully due to VUV emission of noble gas excimers produced in atomic collisions with excited atoms, the latter being in turn produced by drifting electrons. In this work we consider an additional mechanism of proportional electroluminescence, namely that of bremsstrahlung of drifting electrons scattered on neutral atoms (so-called neutral bremsstrahlung); it is systemically studied here both theoretically and experimentally. In particular, the absolute EL yield has for the first time been measured in pure gaseous argon in the two-phase mode, using a dedicated two-phase detector with EL gap optically read out by cryogenic PMTs and SiPMs. We show that the neutral bremsstrahlung effect can explain two intriguing observations in EL radiation: that of the substantial contribution of the non-VUV spectral component, extending from the UV to NIR, and that of the photon emission at lower electric fields, below the Ar excitation threshold. Possible applications of neutral bremsstrahlung effect in two-phase dark matter detectors are discussed.

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1. Introduction

Proportional electroluminescence (EL) in noble gases (or differently secondary scintillation) is the effect that is routinely used

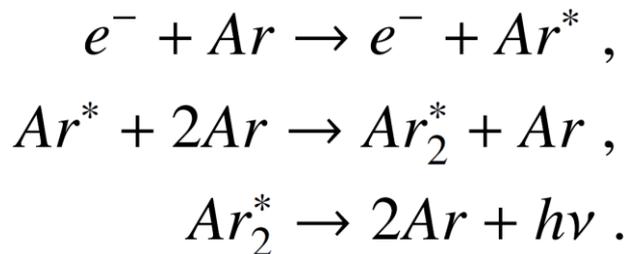
theoretically and experimentally [14,15], little was known about that at cryogenic temperatures. The study of proportional electroluminescence in gaseous Ar at cryogenic temperatures, in the two-phase mode, has been recently started by our (Novosibirsk) group

Motivation

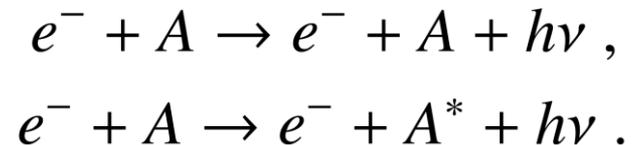
It was believed that proportional electroluminescence (EL) was fully due to VUV emission of noble gas excimers produced in atomic collisions with excited atoms.

On the other hand, our recent experiments have revealed an additional mechanism of proportional EL, namely that of bremsstrahlung of drifting electrons scattered on neutral atoms (so-called neutral bremsstrahlung, NBrS).

Ordinary EL mechanism

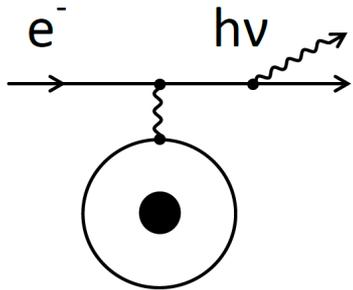
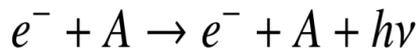


Neutral bremsstrahlung

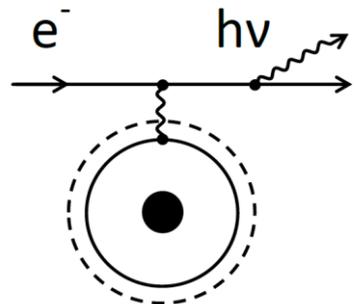
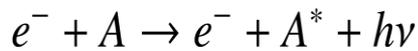


Types of bremsstrahlung

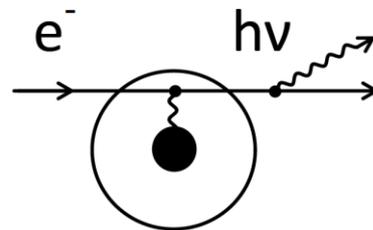
Neutral bremsstrahlung is produced by *slow* (~ 10 eV) electrons when they are scattered (elastically or inelastically) on neutral atoms.



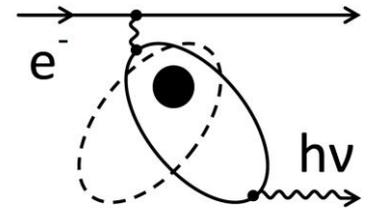
Neutral bremsstrahlung
in elastic scattering



Neutral bremsstrahlung
in inelastic scattering



Ordinary bremsstrahlung



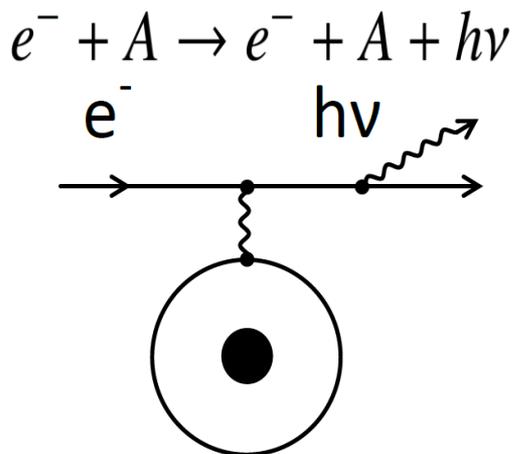
Polarization bremsstrahlung

At such electron energies, the contribution of ordinary bremsstrahlung (produced in the Coulomb field of a nucleus) and polarization bremsstrahlung (produced by atoms due to their time-dependent polarization) is negligible.

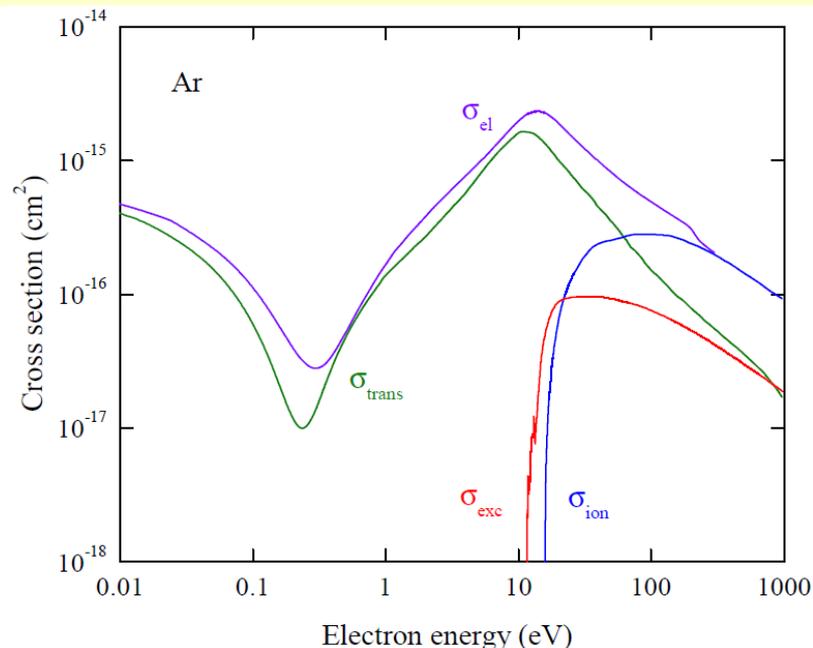
Neutral bremsstrahlung: theoretical predictions

The differential cross section for NBrS photon emission is expressed via elastic cross section (σ_{el}) of electron-atom scattering:

$$\left(\frac{d\sigma}{d\nu}\right)_{NBrS,el} = \frac{8 r_e}{3} \frac{1}{c} \frac{1}{h\nu} \left(\frac{E - h\nu}{E}\right)^{1/2} \times \\ \times [(E - h\nu) \sigma_{el}(E) + E \sigma_{el}(E - h\nu)]$$

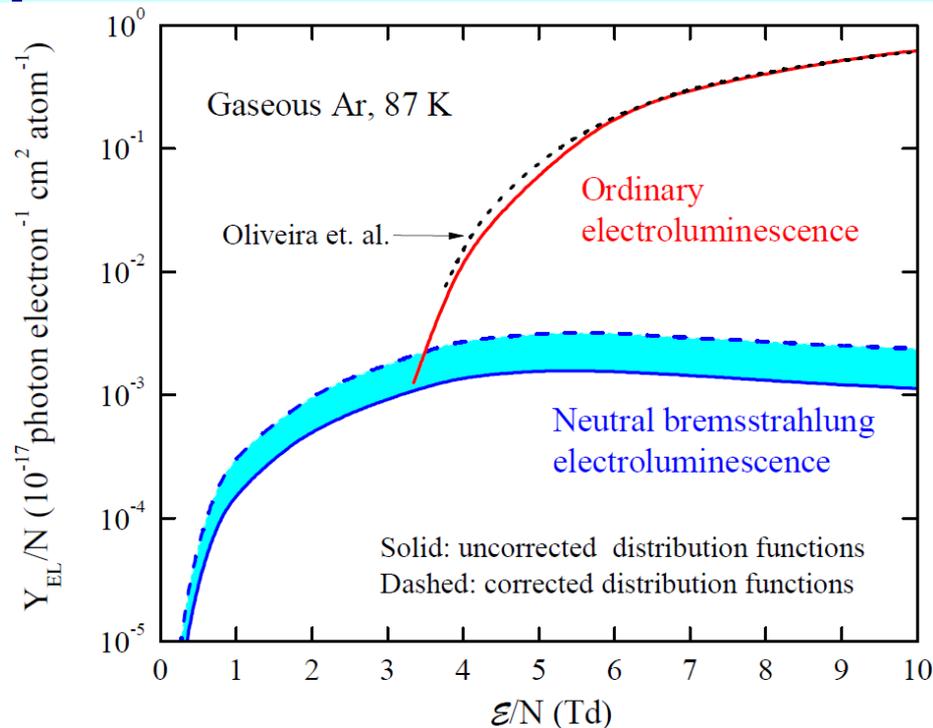
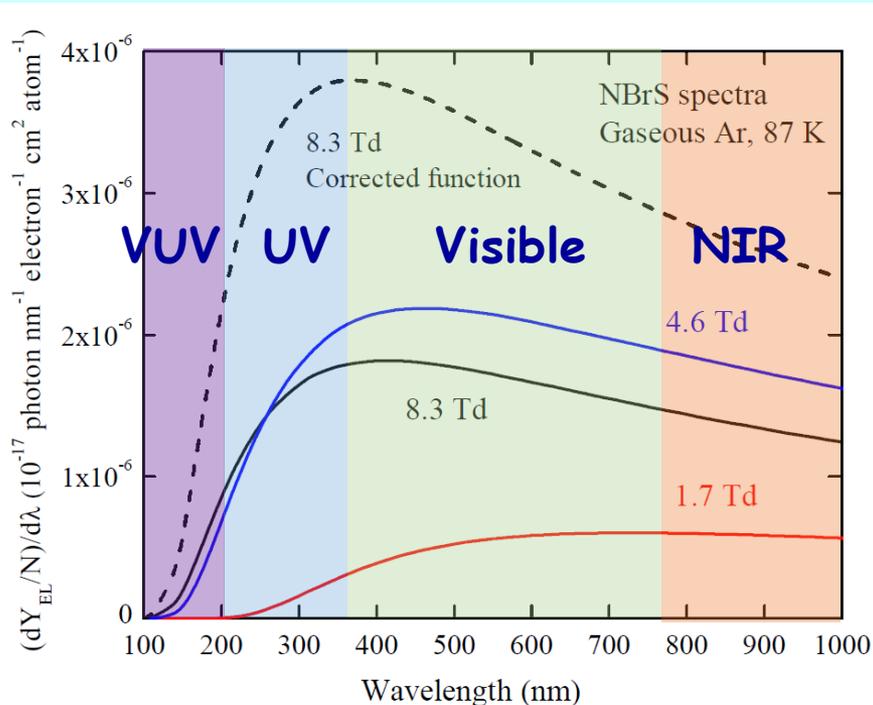


Neutral bremsstrahlung
in elastic scattering



Using this cross section and electron energy distribution functions, we calculated the spectra of NBrS emission at different reduced electric fields E/N (expressed in Td). 1 Td corresponds to electric field of 0.87 kV/cm at 87 K.

Neutral bremsstrahlung vs ordinary EL: theoretical predictions

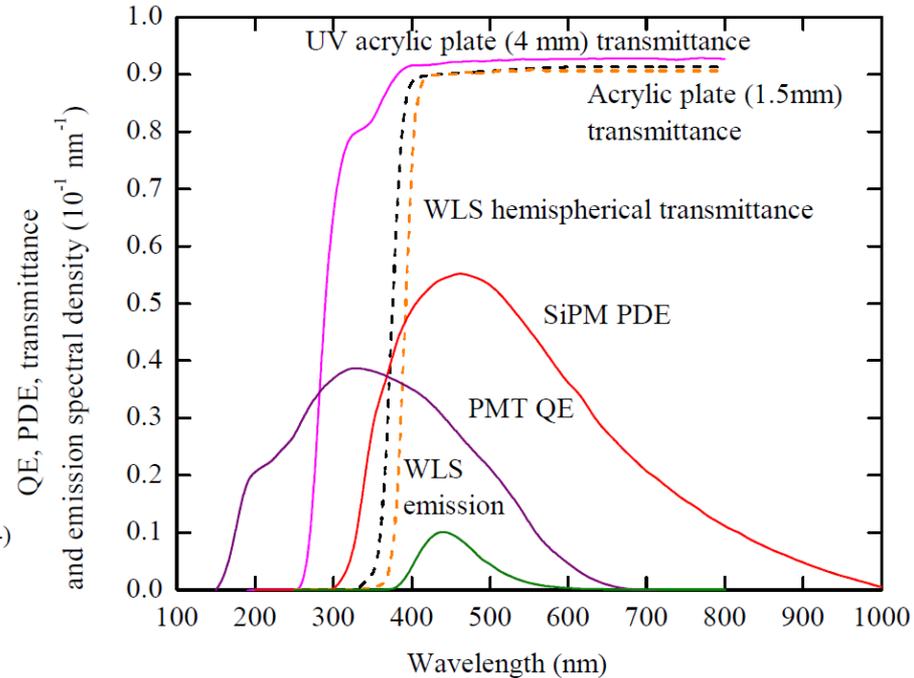
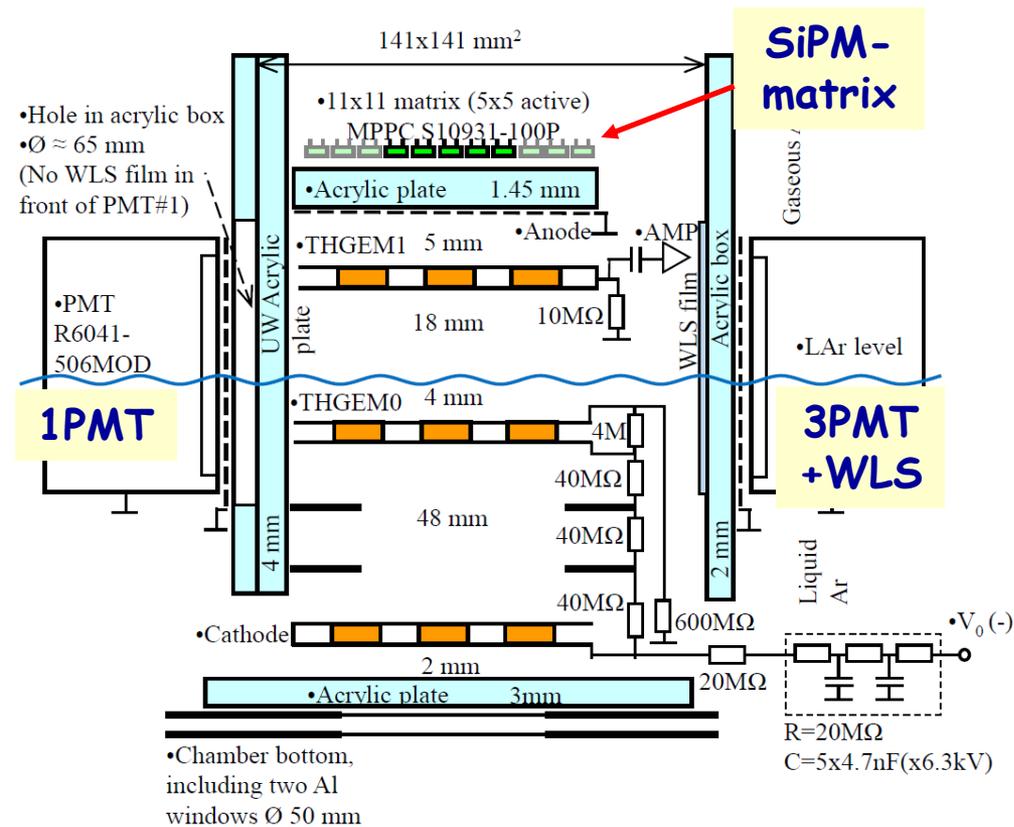


The reduced ordinary EL yield and that of neutral bremsstrahlung at 0-1000 nm in gaseous Ar as a function of the reduced electric field.

Summarizing, the theory of NBrS EL predicts:

- 1) electroluminescence below the Ar excitation threshold (~ 4 Td), in the UV, visible and NIR regions;
- 2) appreciable non-VUV component above the Ar excitation threshold, extending from the UV to NIR.

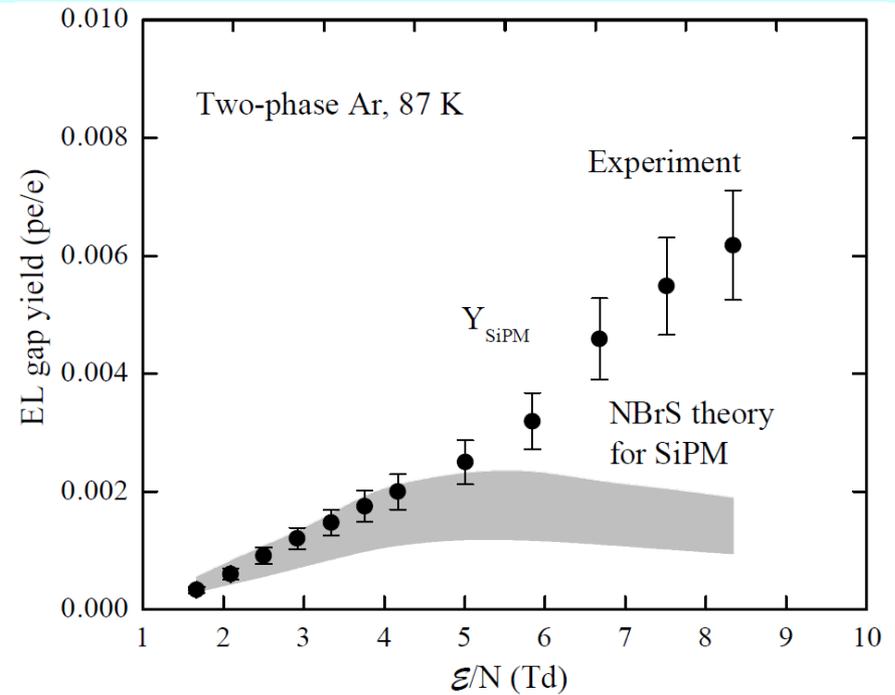
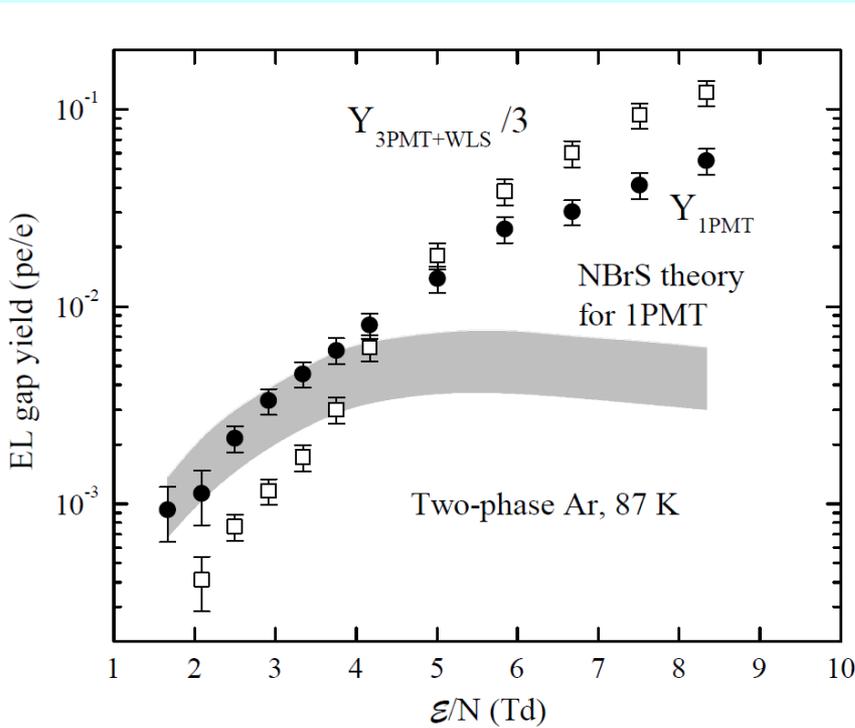
Experimental setup



Taking into account light propagation through acrylic plates and WLS, the detectors were sensitive in the following wavelength regions:

- 1PMT (bare PMT):** 300-650 nm (via direct recording)
- 3PMT+WLS:** 100-650 nm (at <400 nm via re-emission in WLS, at >400 nm via direct recording)
- SiPM-matrix:** 400-1000 nm (via direct recording)

EL gap yield for PMT



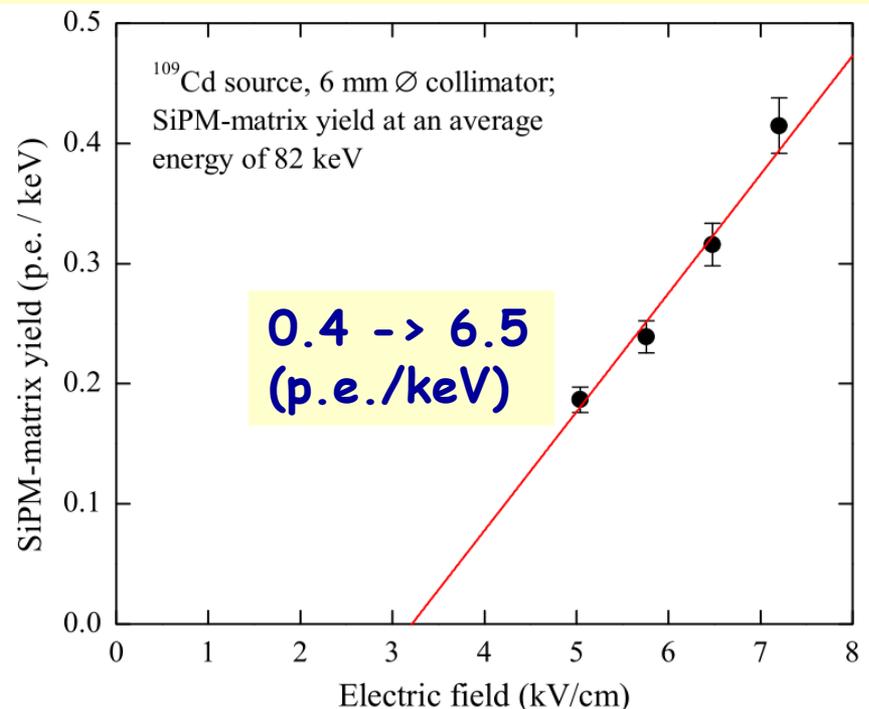
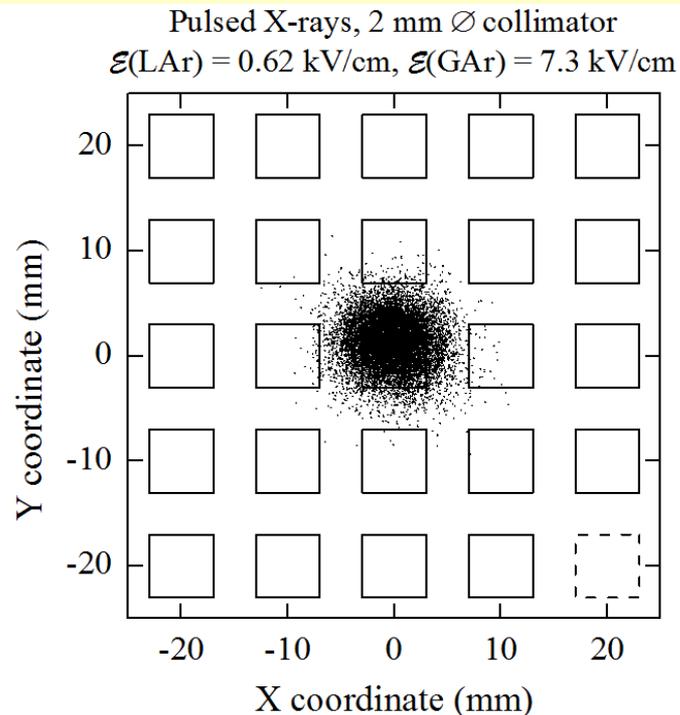
A close examination reveals two remarkable properties of proportional EL.

- 1) there is an under-threshold EL below the Ar excitation threshold (at 4 Td), where the non-VUV component fully dominates.
- 2) there is an appreciable contribution of the non-VUV component above the threshold.

Direct readout on SiPM-matrix using NBrS EL

The next figures illustrate the performance of our two-phase TPC with direct optical readout of the EL gap using SiPM-matrix.

The left figure shows the coordinate distribution of reconstructed events. The right figure shows the light yield vs the electric field. The maximum light yield is only 0.4 p.e./keV. This is because our detector operated in non-optimal conditions: this value is expected to be increased up to 6.5 p.e./keV.



Summary

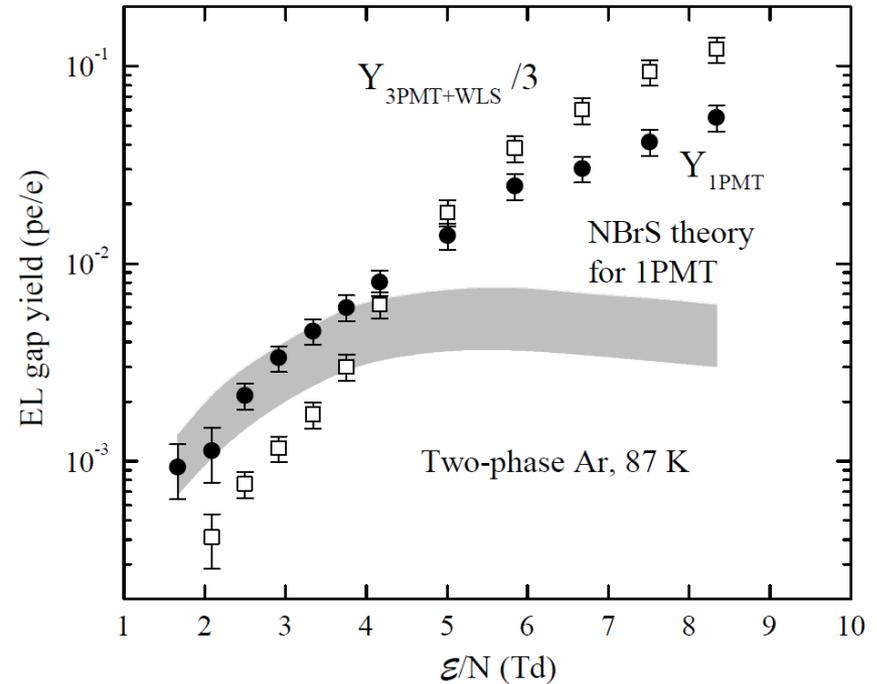
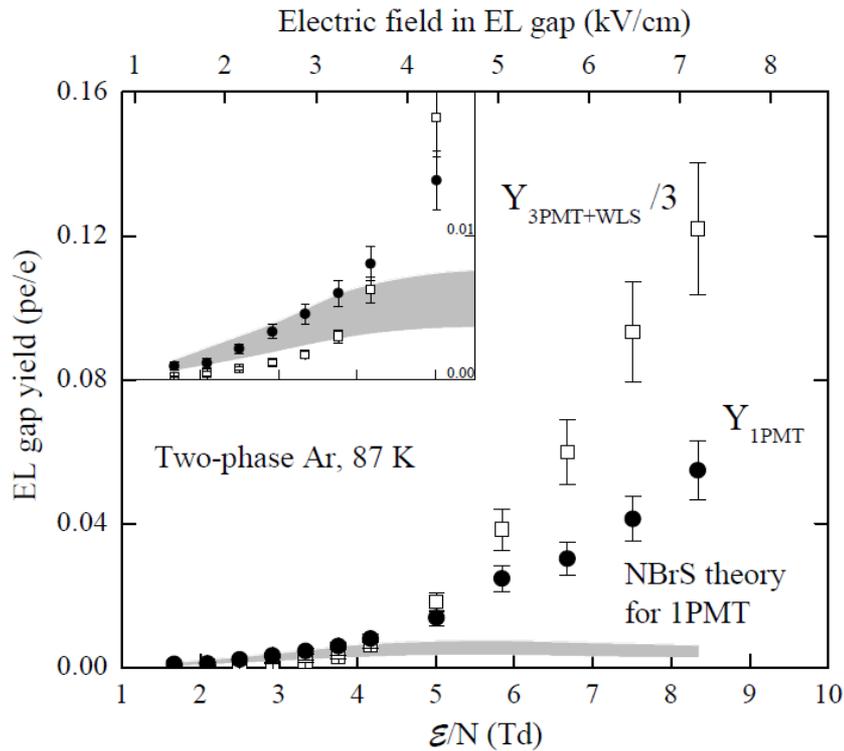
An additional mechanism of proportional electroluminescence (EL) in two-phase dark matter detectors, namely that of neutral bremsstrahlung (NBrS), has been studied. It explains the non-VUV spectral component and photon emission below the Ar excitation threshold.

The merit of the present work is that it transformed the idea of NBrS electroluminescence from a hypothesis into a quantitative theory.

One of the possible applications of NBrS EL is the opportunity of direct (without WLS) optical readout using PMTs and SiPM-matrices: at the electric field in the EL gap close to the EL threshold (~ 4 Td), the light yield of direct readout is comparable to that of readout with WLS.

Backup slides

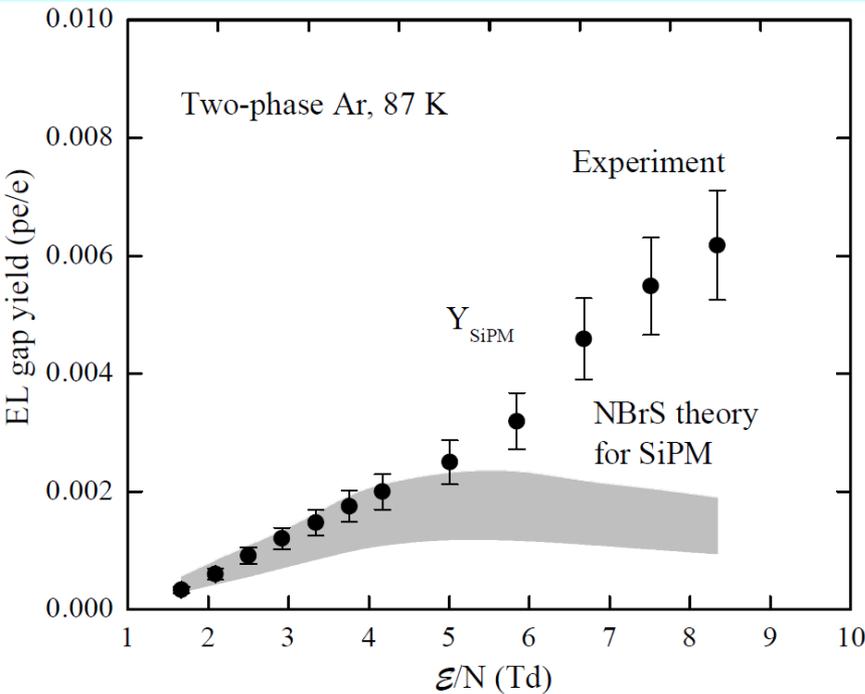
EL gap yield for PMT



A close examination reveals two remarkable properties of proportional EL.

- 1) there is an under-threshold EL below the Ar excitation threshold (at 4 Td), where the non-VUV component fully dominates.
- 2) there is an appreciable contribution of the non-VUV component above the threshold.

EL gap yield for SiPM-matrix

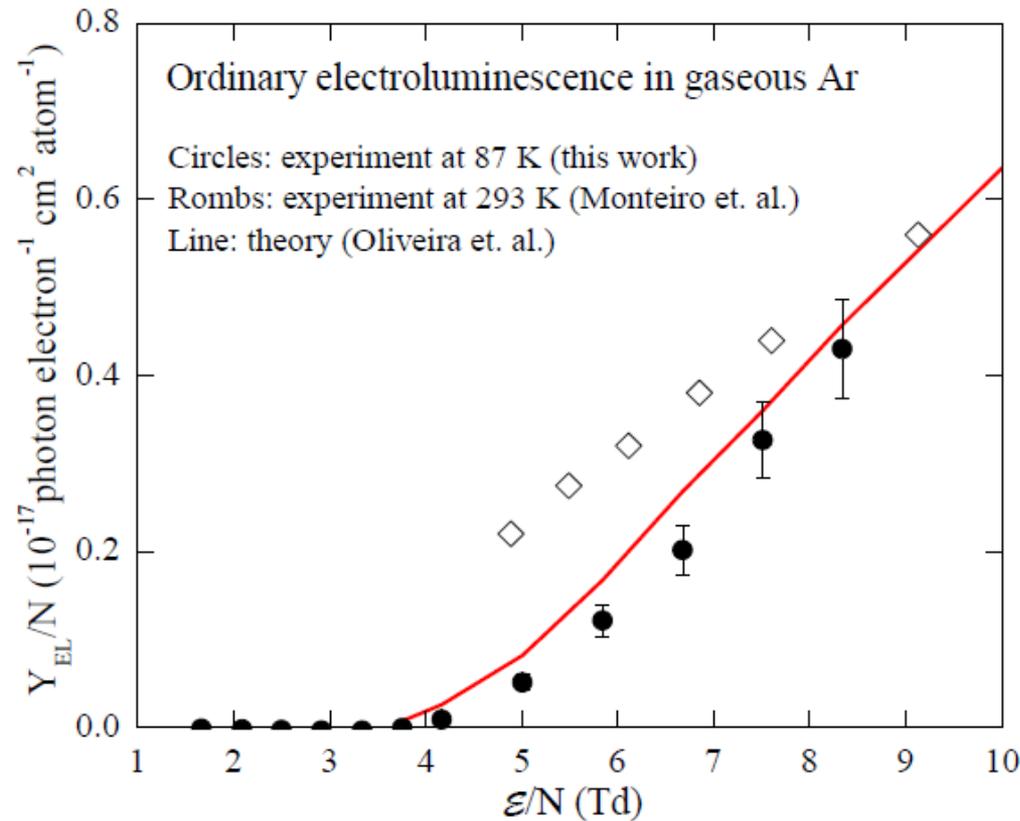


EL gap yield for SiPM readout fully confirms the results of 1PMT readout:

- electroluminescence below the threshold;
- constantly increasing EL yield above the threshold.

Above the threshold, the theory quickly diverges from experiment. Back in 80s, it was suggested how to eliminate such a discrepancy: electron trapping at Feshbach resonance energies leads to enrichment of the high-energy tail of the electron energy distribution function and NBrS yield at resonance is significantly (>3 times) enhanced.

Reduced EL yield in the VUV



Reduced EL yield for ordinary (VUV) electroluminescence, obtained in this work, was compared to the yields at room T, obtained experimentally and theoretically [Oliveira 2011].

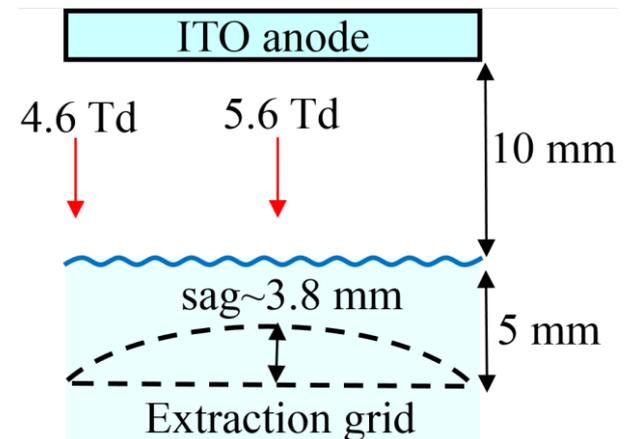
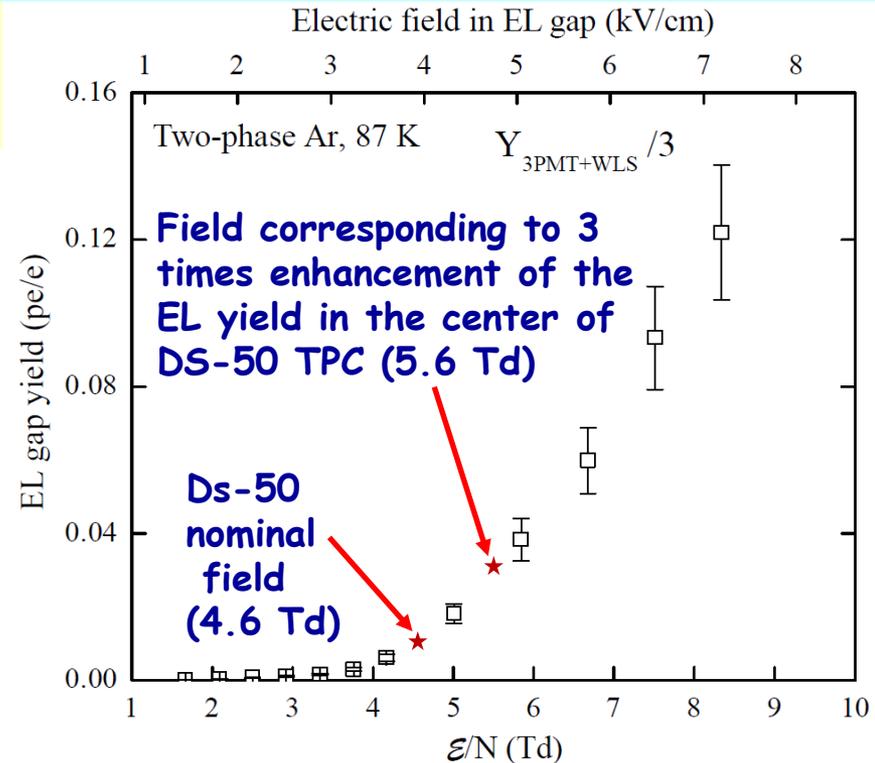
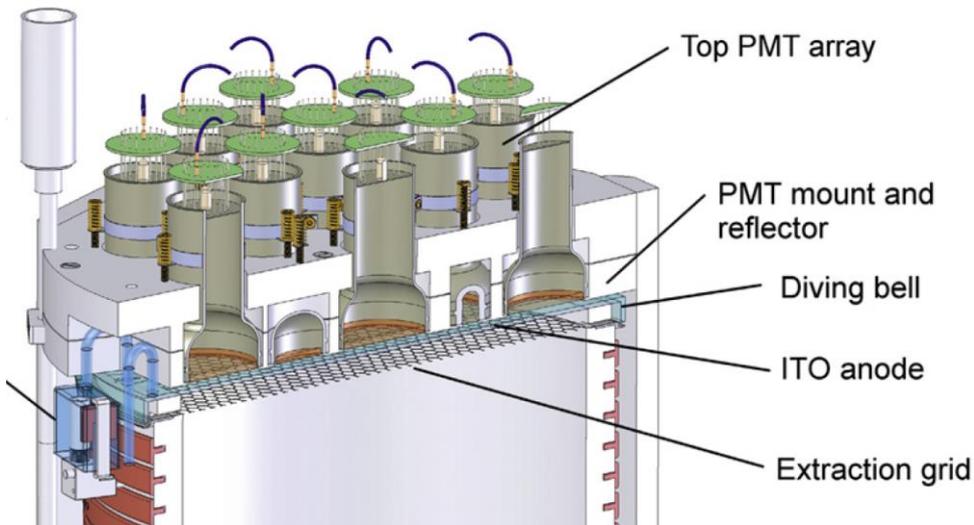
This figure demonstrates a convincing agreement between the theory and our experiment, the latter using NBrS paradigm in proportional EL.

Estimation of extraction grid sagging

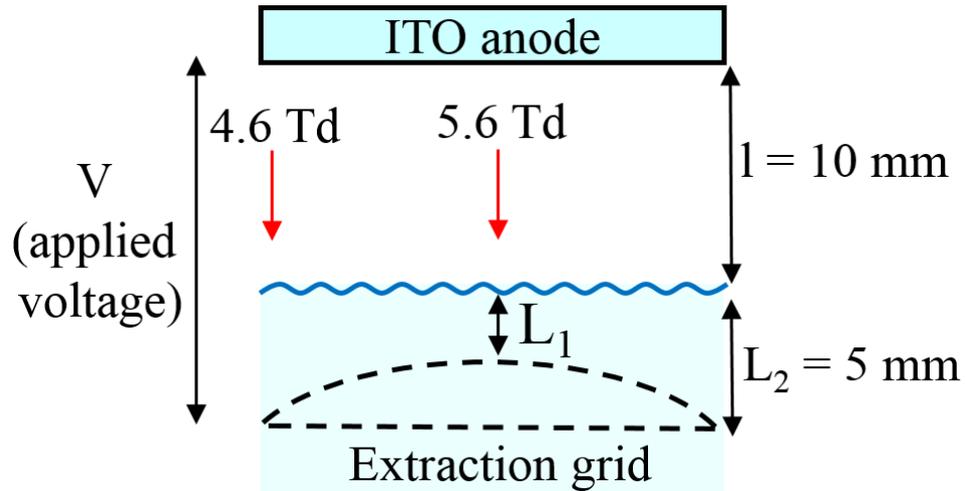
DS-50: First results from the DarkSide-50... Phys.Let.B. 2015

"...S2 has a strong radial dependence, where events under the central PMT exhibit greater than three times more electroluminescence light than events at the maximum radius."

DarkSide-50 TPC operated at nominal EL electric field of 4.6 Td.



Estimation of extraction grid sagging



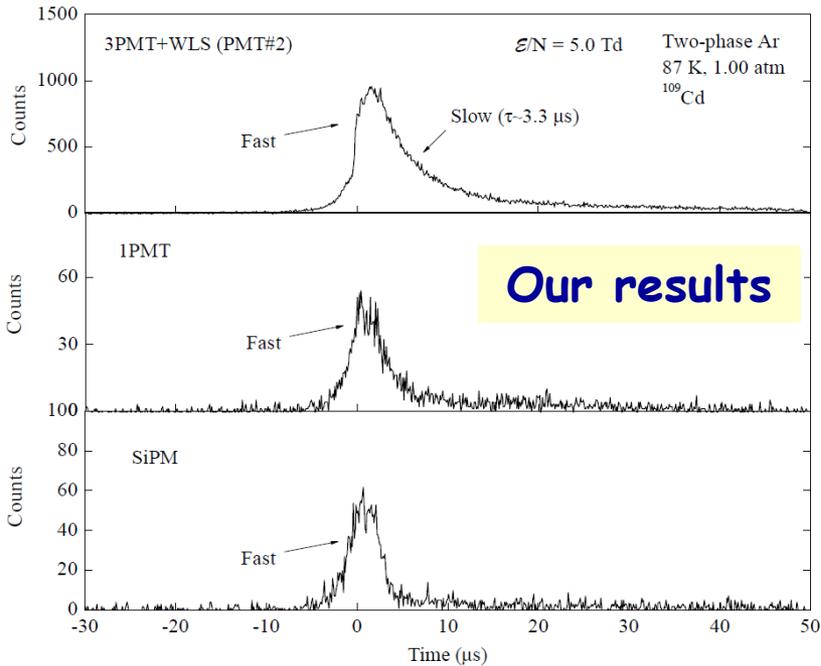
$$E(\text{field}) = V / (L/\epsilon + l)$$

$$\frac{E_1}{E_2} = \frac{L_2/\epsilon + l}{L_1/\epsilon + l}$$

$$L_1 = \left[\left(L_2/\epsilon + l \right) / \frac{E_1}{E_2} - l \right] \epsilon$$

$$\text{sag} = (L_2 - L_1) \sim 3.8 \text{ mm}$$

Pulse shape: fast component fraction



In DarkSide-50 the fast component fraction was taken $p=10\%$ (using ordinary EL approach). According to our data and using NBrS paradigm, this fraction is predicted to be substantially larger, varying from about $60 \pm 5\%$ to $45 \pm 5\%$ at DS-50 fields (4.6-5.6 Td).

This enhancement can affect the determination of the quantities using the fast component, such as the diffusion coefficients in liquid Ar or z-coordinate fiducialization.

DS-50: Electroluminescence pulse shape... arXiv:1802.01427v1

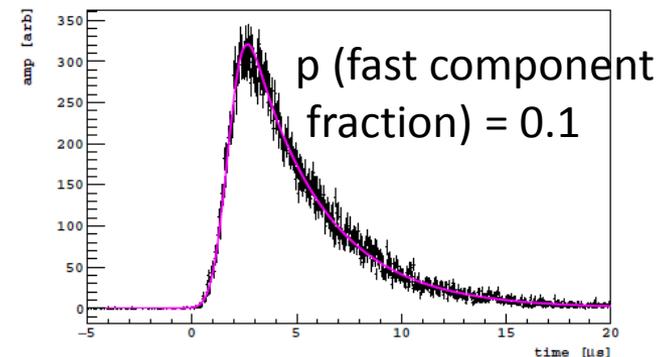
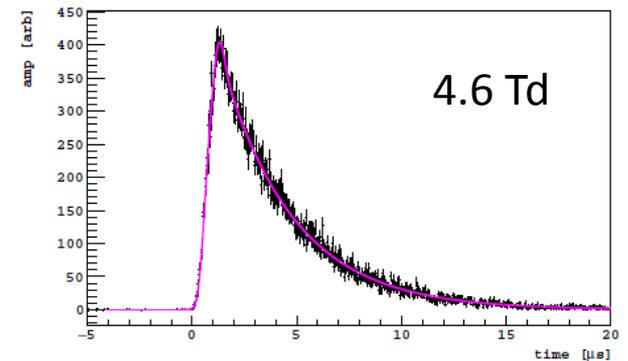
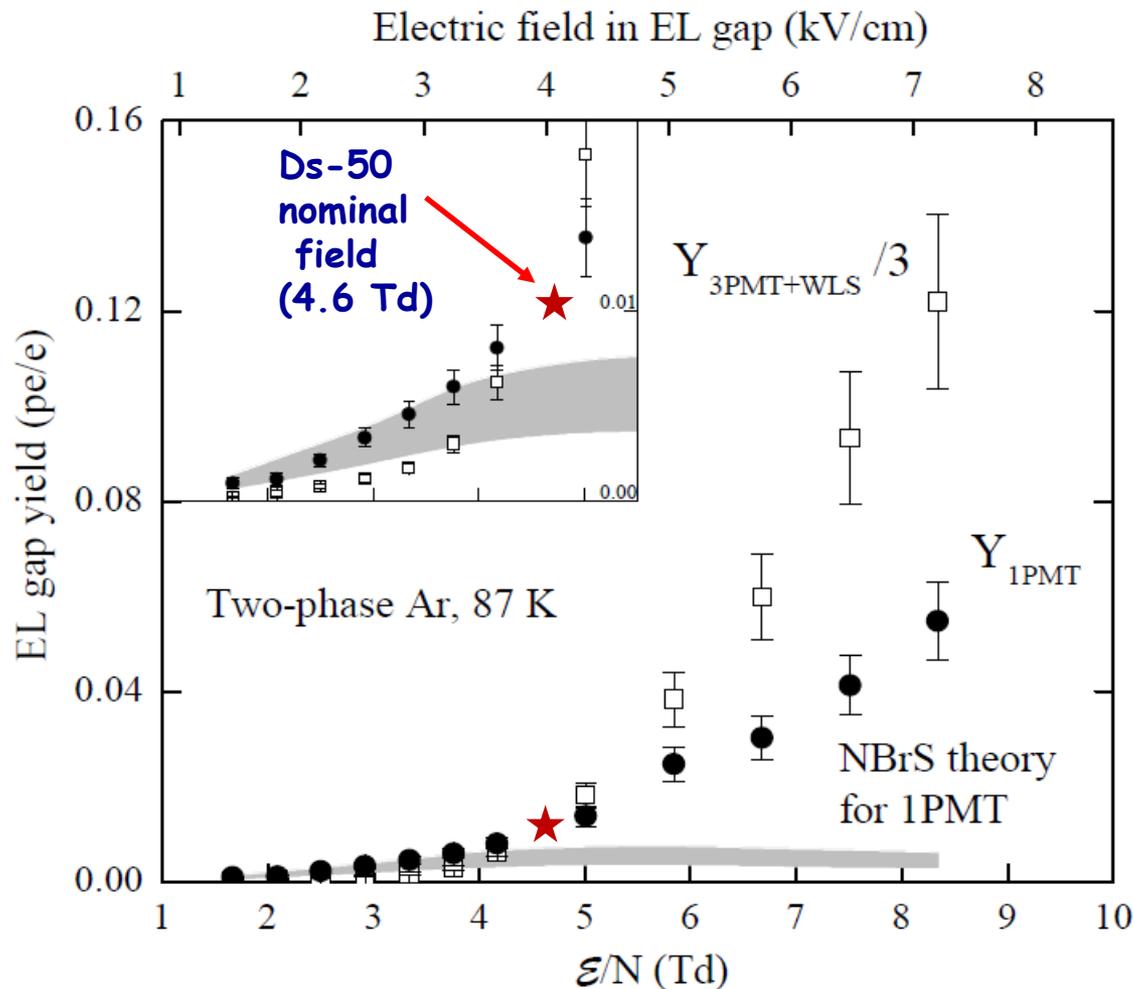


FIG. 8: Examples of S2 pulse shape fits for the electron diffusion measurement. Top: Event with a $22 \mu\text{s}$ drift time. Bottom: Event with a $331 \mu\text{s}$ drift time. The waveforms have been re-binned to 32 ns sampling, and the x-axes redefined such that $t = 0$ is at the S2 start time.

Direct readout using NBrS EL

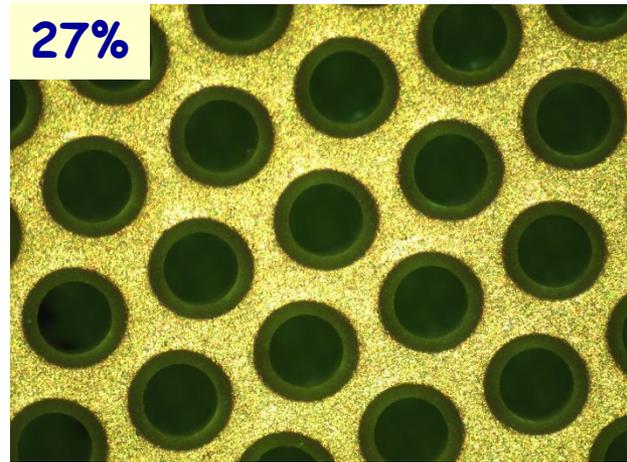
Another implication for DarkSide is the opportunity for direct (without WLS) optical readout using PMTs and SiPM-matrices: at DS-50 nominal electric fields in the EL gap (4.6 Td), the light yield of direct readout is equal to that of the readout with WLS.



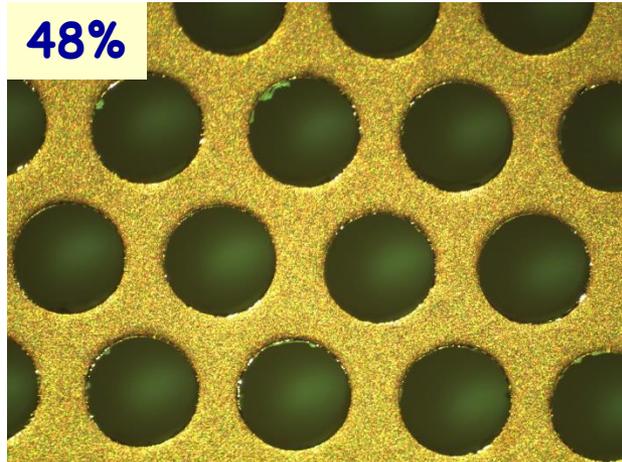
Estimation of extraction grid sagging

It's possible to use THGEM as an extraction grid.

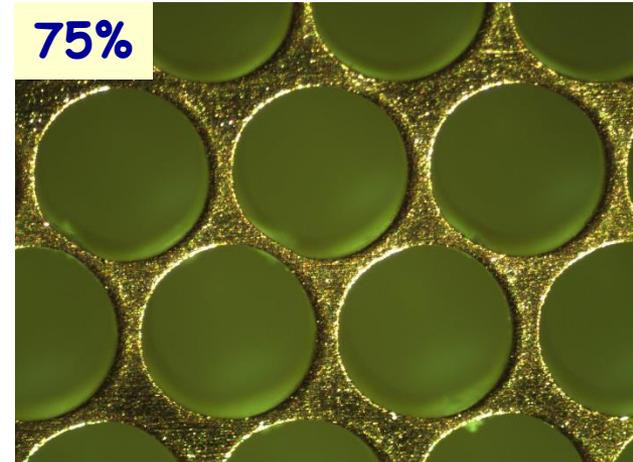
27%



48%



75%



Pulse shape: fast component fraction

$$p_{DS-50} = OEL_{fast} / (OEL_{fast} + OEL_{slow}) \sim 0.1$$

OEL_{fast} - Ordinary EL, fast component (11 ns)

OEL_{slow} - Ordinary EL, slow component (3.2 us)

$$OEL_{fast} + OEL_{slow} + k * LY_{without\ WLS} \equiv LY_{with\ WLS}$$

$LY_{without\ WLS}$ - Light yield for detector without WLS

$LY_{with\ WLS}$ - Light yield for detector with WLS

$k \sim 0.58$ - Coefficient to account different spectral sensitivity for NBrS for detector with and without WLS

$$p_{new} = (OEL_{fast} + k * LY_{without\ WLS}) / (OEL_{fast} + OEL_{slow} + k * LY_{without\ WLS}) =$$

$$(OEL_{fast} + k * LY_{without\ WLS}) / LY_{with\ WLS} =$$

$$1 - OEL_{slow} / LY_{with\ WLS} =$$

$$1 - [(1 - p_{DS-50}) / (OEL_{fast} + OEL_{slow})] / LY_{with\ WLS} =$$

$$1 - [(1 - p_{DS-50}) / (LY_{with\ WLS} - k * LY_{without\ WLS})] / LY_{with\ WLS} =$$

$$1 - (1 - p_{DS-50}) (1 - k * LY_{without\ WLS} / LY_{with\ WLS})$$

NBrS EL theory: basic equations

$$\left(\frac{d\sigma}{dv}\right)_{NBrS,el} = \frac{8}{3} \frac{r_e}{c} \frac{1}{h\nu} \left(\frac{E - h\nu}{E}\right)^{1/2} \times [(E - h\nu) \sigma_{el}(E) + E \sigma_{el}(E - h\nu)]$$

$$\frac{dI_{ph}(\lambda)}{d\lambda} = \frac{dN_{ph}}{dt N_e dV d\lambda} = N \int_{h\nu}^{\infty} v_e \frac{d\sigma}{dv} \frac{dv}{d\lambda} f(E) dE$$

in photon/(s nm electron) ,

$$\left(\frac{Y_{EL}}{N}\right)_{NBrS} = \frac{dN_{ph}}{dx N N_e dV} = \frac{1}{v_d N} \int_{\lambda_1}^{\lambda_2} \frac{dI_{ph}(\lambda)}{d\lambda} d\lambda = \int_{\lambda_1}^{\lambda_2} \int_{h\nu}^{\infty} \frac{v_e}{v_d} \frac{d\sigma}{dv} \frac{dv}{d\lambda} f(E) dE d\lambda$$

in (photon cm²)/(electron atom)

$$\frac{d(Y_{EL}/N)_{NBrS}}{d\lambda} = \int_{h\nu}^{\infty} \frac{v_e}{v_d} \frac{d\sigma}{dv} \frac{dv}{d\lambda} f(E) dE$$

in (photon cm²)/(electron atom nm) ,

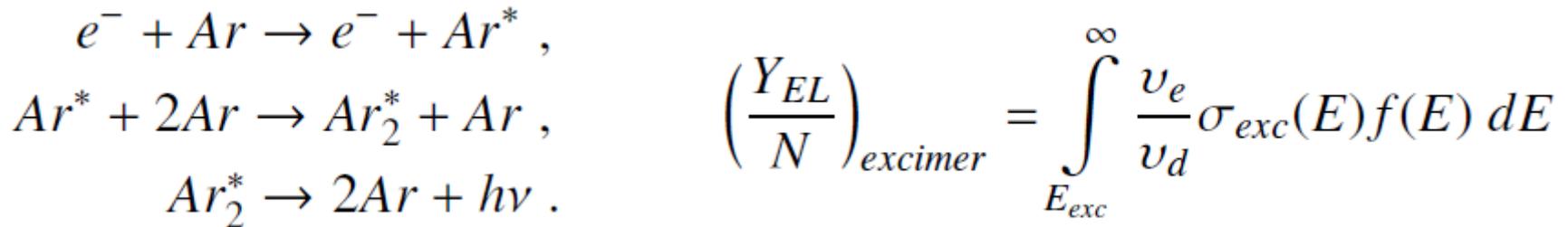
NBrS EL theory: basic equations

$$\int_0^{\infty} f(E) dE = 1$$

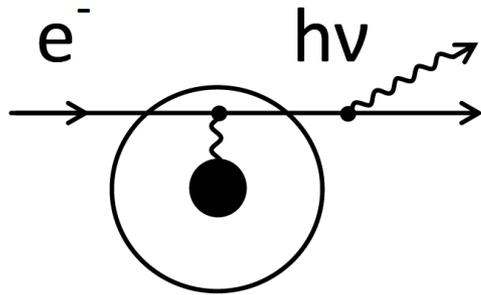
$$\int_0^{\infty} E^{1/2} f'(E) dE = 1$$

Electron energy distribution function normalization: two ways

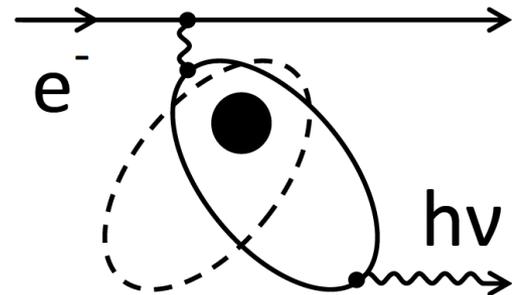
Electron energy distribution functions was calculated using Boltzmann equation solver BOLSIG+ (free software)



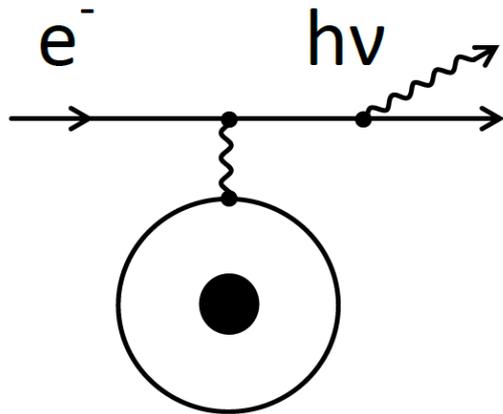
Ordinary electroluminescence, involving excimers



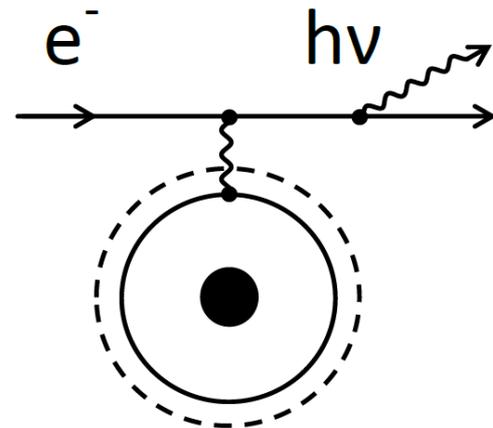
Ordinary bremsstrahlung



Polarization bremsstrahlung

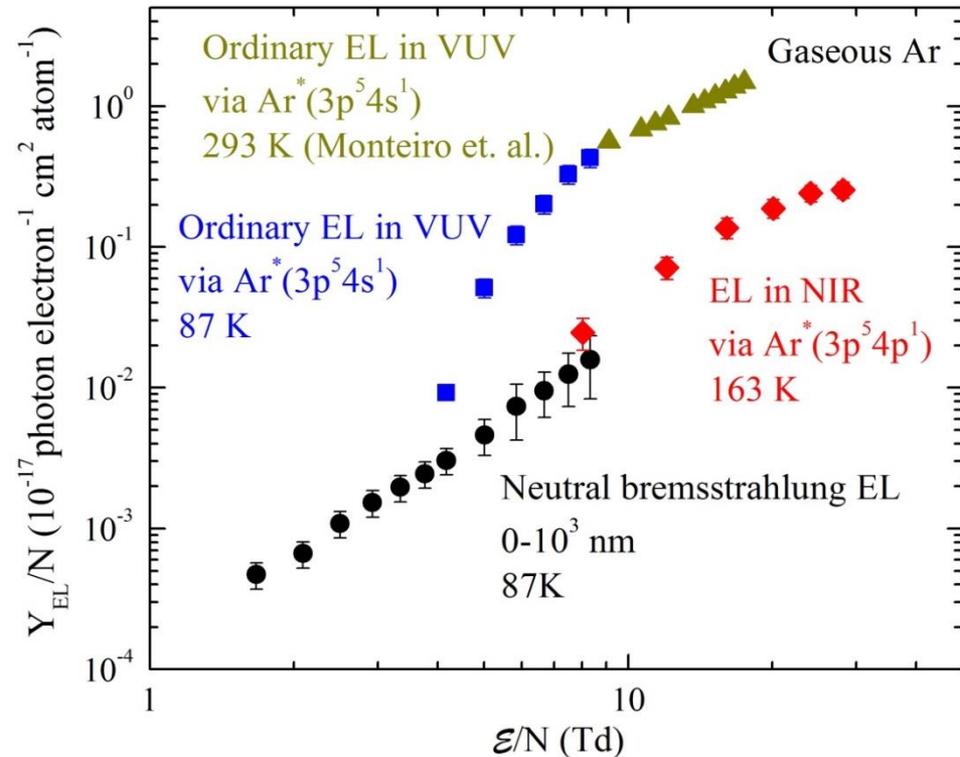
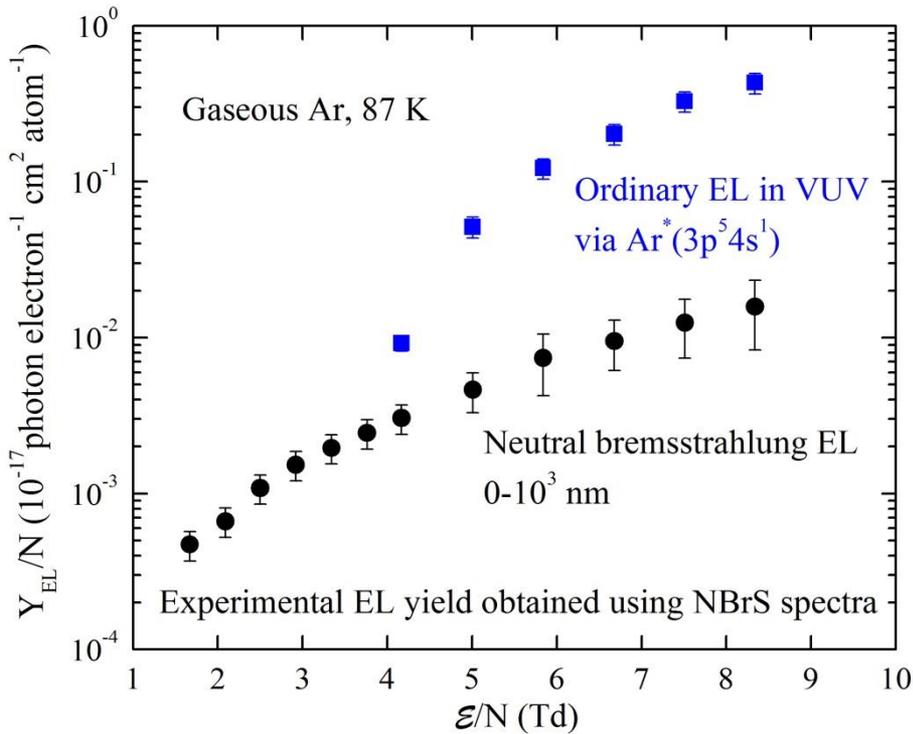


Neutral bremsstrahlung
in elastic scattering

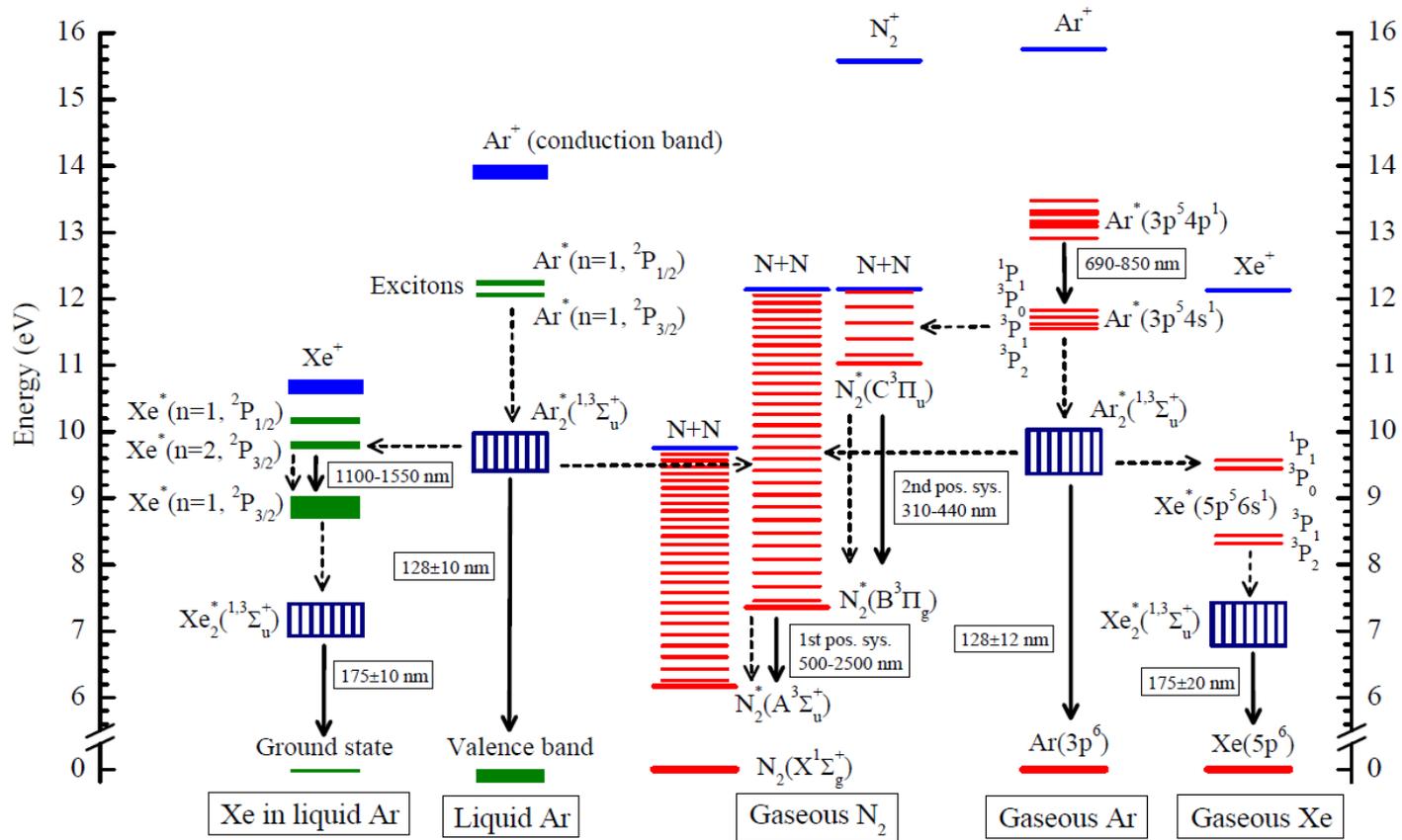


Neutral bremsstrahlung
in inelastic scattering

Summary of experimental EL yield in gaseous Ar



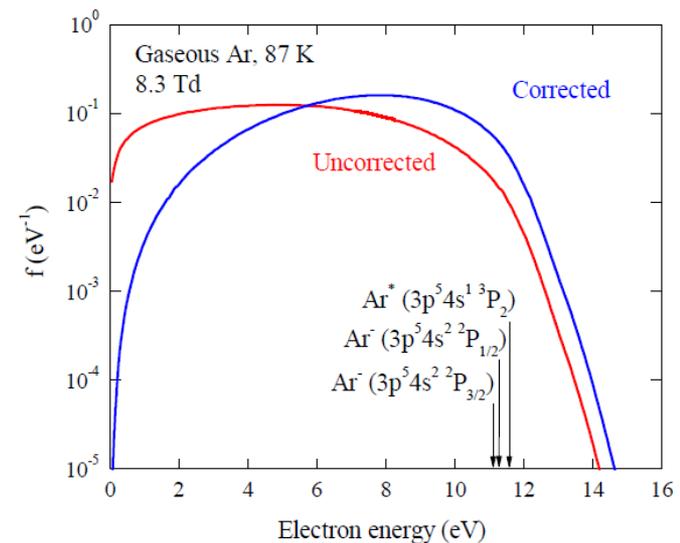
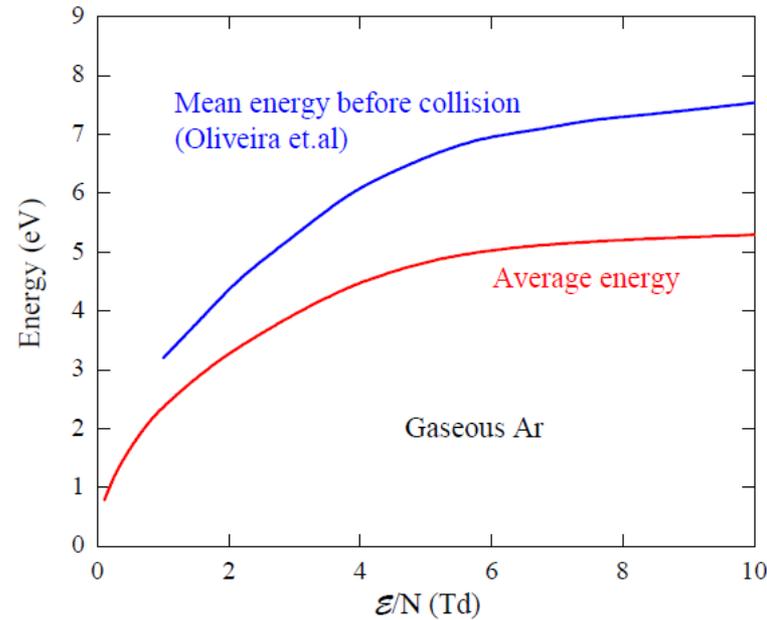
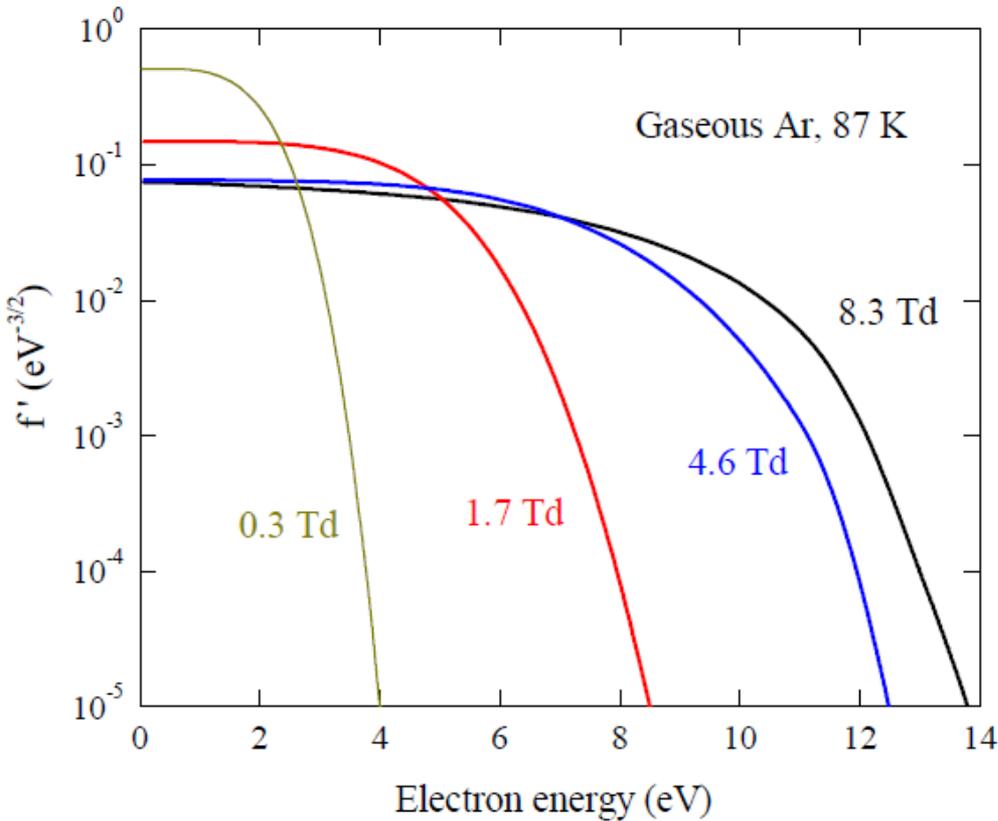
The problem of doping Ar with Xe and N₂



• Photon emission and atomic collision processes in two-phase argon doped with xenon and nitrogen: the most complete compilation over past 50 years (A. Buzulutskov, Eprint 1702.03612).

• The problem is currently under study in our group. You can find details in the article.

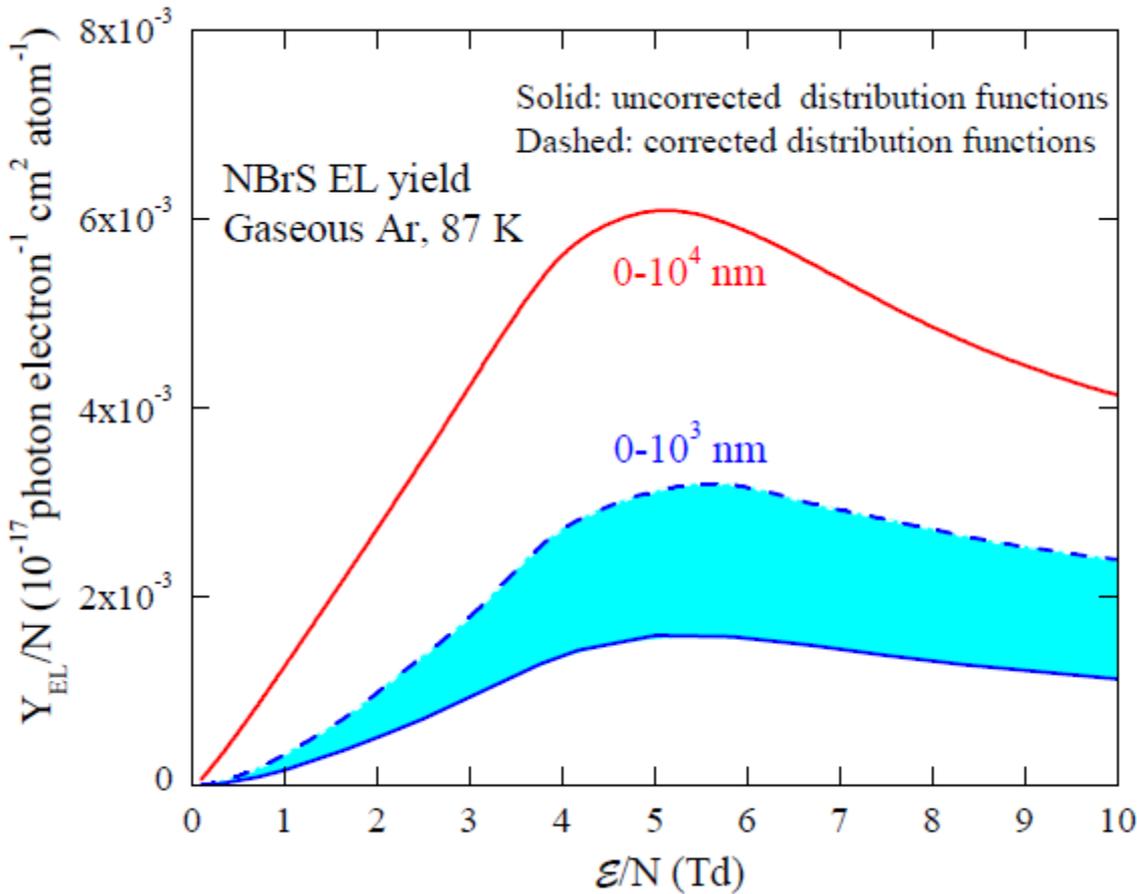
NBrS EL theory: electron energy distribution functions



Electron energy distribution functions, calculated using Boltzmann equation solver BOLSIG+ (free software)

E/N is expressed in Td.
1 Td = 10^{-17} V cm^2 atom^{-1} , corresponding to ~ 0.87 kV/cm in gaseous Ar at 87 K.

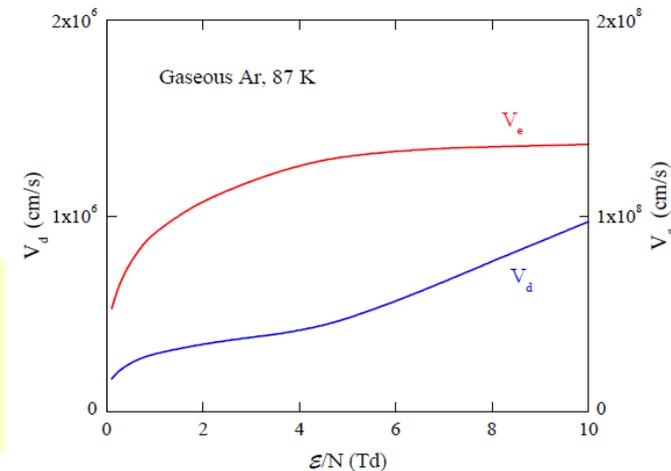
NBrS EL theory: EL yield field dependence



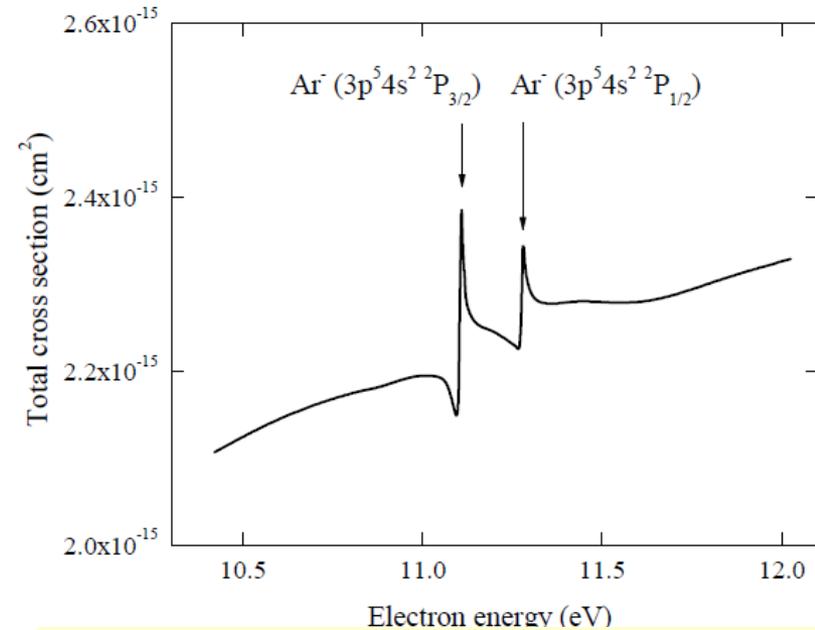
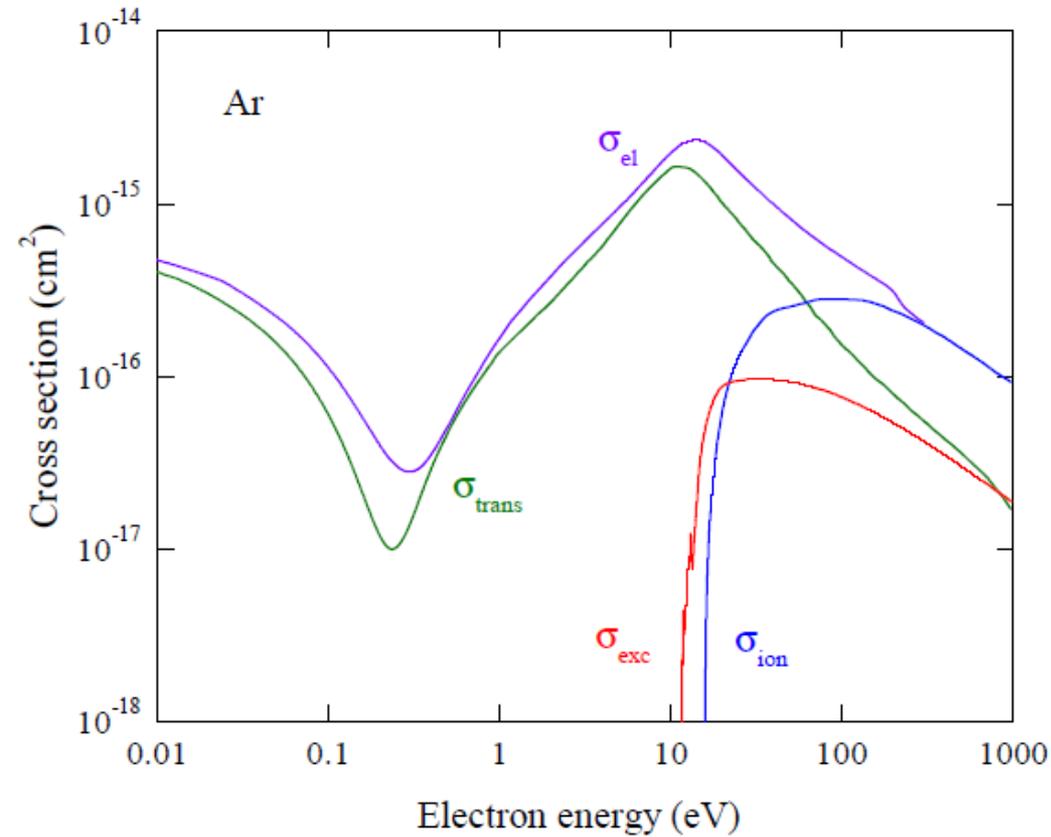
Baseline theoretical scenario

NBrS EL yield in the 0-1000 nm range represents the maximum number of NBrS photons that can ever be detected by existing devices.

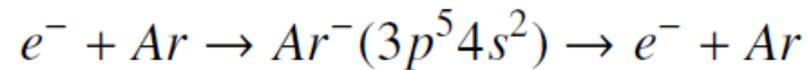
NBrS EL yield first increases, then saturates and even decreases with the field: this reflects v_e/v_d behavior →



NBrS EL theory: cross-sections



Experimental cross-section for electron scattering from Ar around Feshbach resonances [Kurokawa 2011]



Electron scattering cross-sections in Ar obtained from the last version of Magboltz

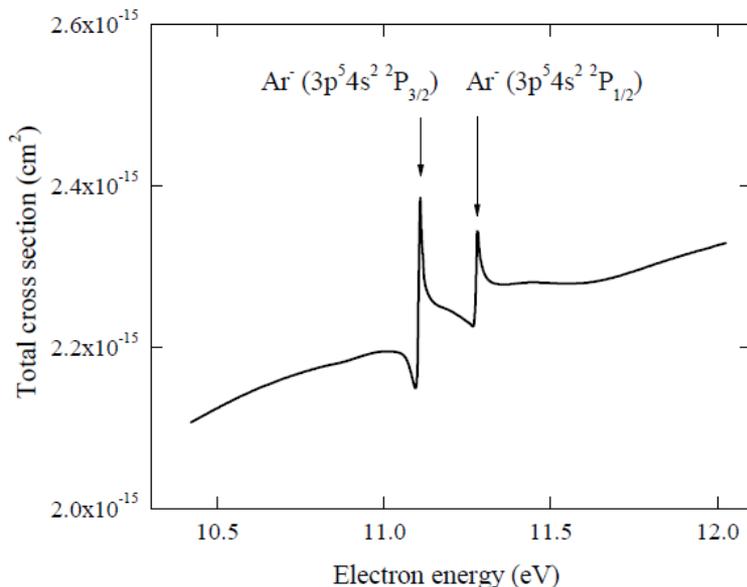
Hypothesis of electron resonance trapping

Mechanism of electron resonance trapping:

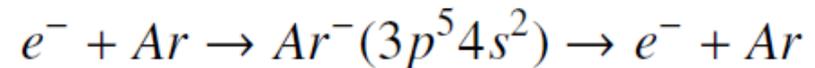
G.M. De'Munari et al., Electroluminescence of rare gases and electron bremsstrahlung, Lett. Nuov. Cimento 2 (1971) 68

G.M. De'Munari et al., Effects of molecular gases on Xe electroluminescence and electron resonance trapping, Nuov. Cimento 3 (1984) 963

When the electron, accelerated by the electric field between the collisions, reaches the resonance energy, with high probability it is captured to form a negative ion state Ar^- . The electron spends there a certain time, of about 0.5 ps, and then releases at somewhat lower energy, since part of the energy is transferred to the atom. Then the cycle repeats, which finally leads to trapping of a part of the electrons at the resonance energy and thus to the enrichment of the high-energy tail of the electron energy distribution function.



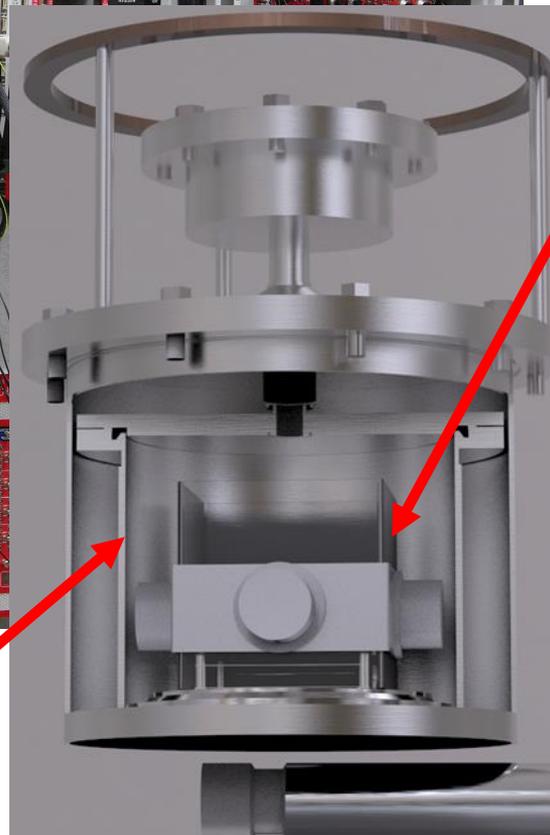
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Experimental setup



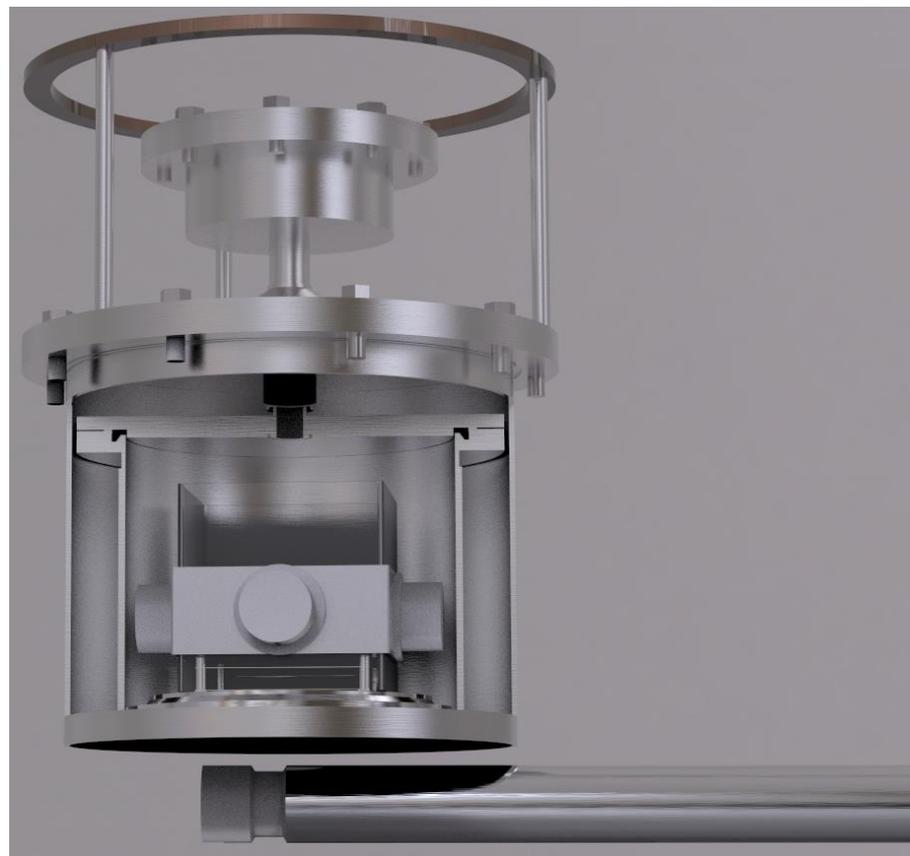
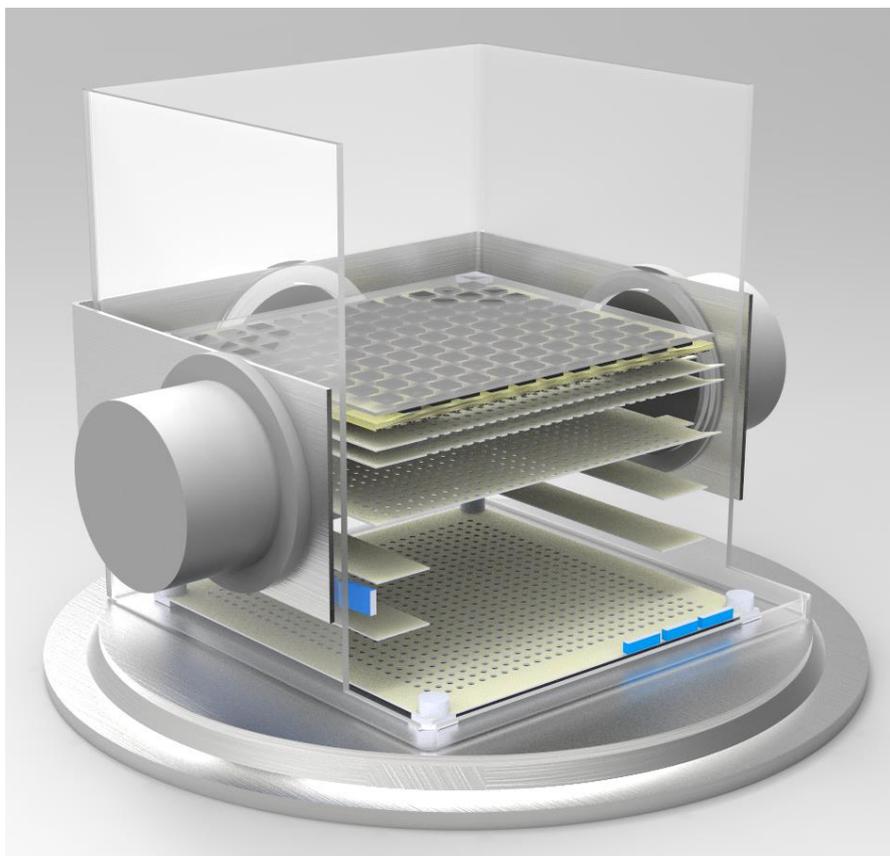
Assembly with EL gap and PMT readout



Neutron generator

A vacuum-insulated 9-liter two-phase cryogenic chamber filled with 2.5 liters of liquid Ar

Chamber 3D - view



Optical spectra

