Neutral Bremsstrahlung in Time Projection Chambers

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Outline

- Experimental evidence

- What is neutral bremsstrahlung (NBRS)
- Theory of NBRS
- Computing NBRS

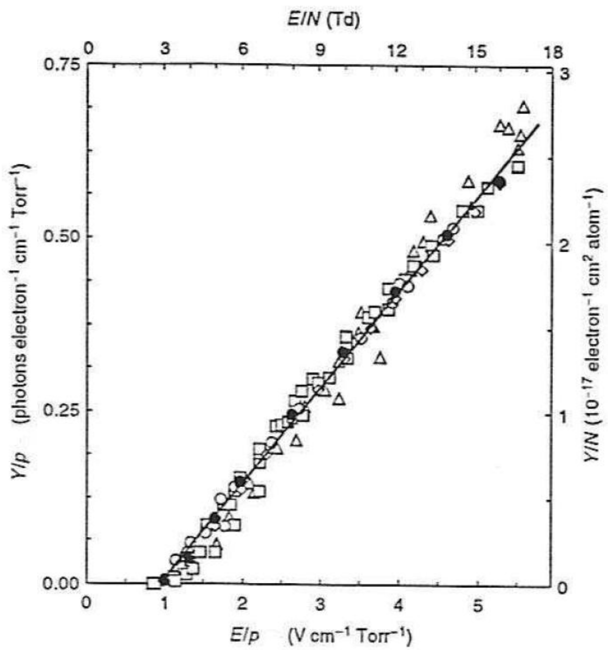
- Comparison with experimental results
- Simulations of pure noble gases
- Simulations of noble gas mixtures

- Liquid elements cross sections
- Liquid elements drift parameters
- Comparison liquid-gas
- Simulation of liquid elements

Experimental evidence

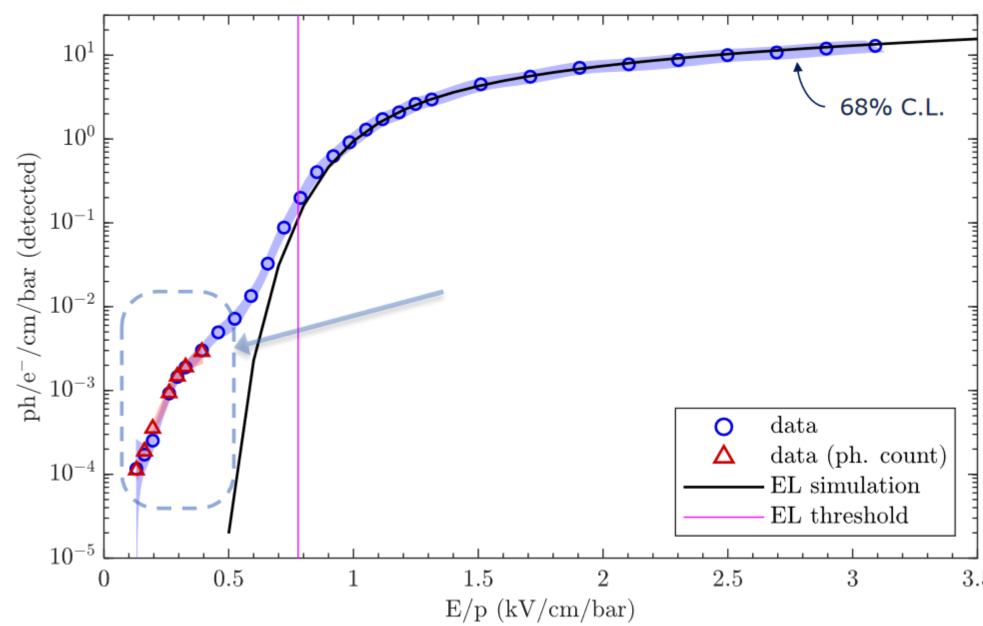
- Results by groups in Novosibirsk and Coimbra/Santiago point towards sub threshold emission

Aprile, Noble Gas Detectors



$$dN_{ph}/dx = 70(E/p - 1.0)p$$

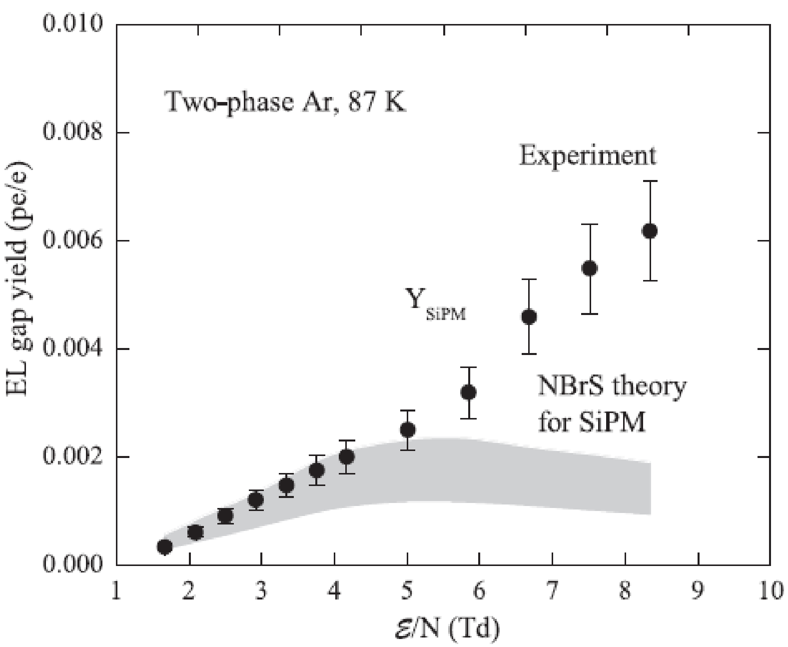
Carlos A. O. Henriques et al, 2020, RD51 collaboration meeting



Experimental evidence

- Results by groups in Novosibirsk and Coimbra/Santiago point towards sub threshold emission

Buzulutskov et al, 2018
arXiv:1803.05329



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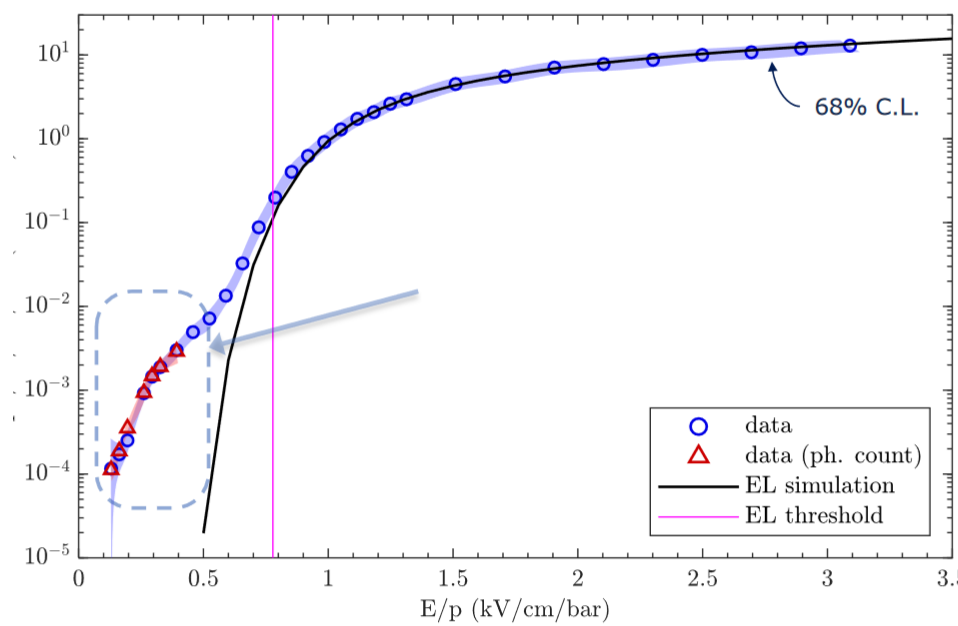
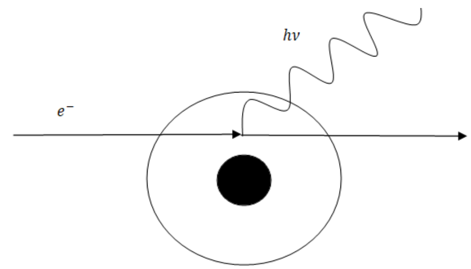


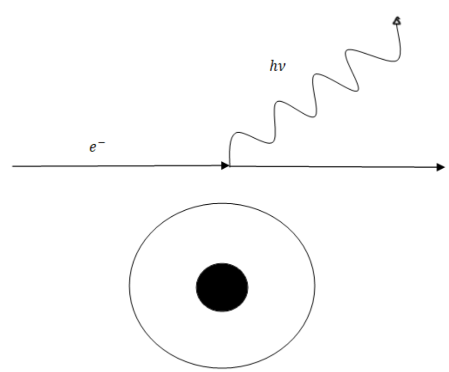
What is NBRS

- Ordinary bremsstrahlung is the photon emission by an electron interacting with the coulomb field of the nucleus



Bremsstrahlung

- Neutral bremsstrahlung (NBRS) is the emission of photons by the electrons when interacting with the dipole field of the atom



Neutral Bremsstrahlung

Theory of NBRS

- Assume an electron with energy E_i momentum k_i and wavefunction $\psi_i(\vec{r})$ undergoes a transition to a new state $\psi_f(\vec{r})$ with energy E_f and momentum k_f

- The emission cross section

$$\frac{d\sigma}{d\nu} = \frac{8\pi e^2 \nu^3 m_e^2 k_f}{3\hbar^3 c^3 k_i}|M|^2 \quad \text{with} \quad |M|^2 \equiv |\langle \Psi_f | \vec{r} | \Psi_i \rangle|^2$$

- To calculate M, we can resort to the partial waves method and use some approximations to avoid doing the full calculation

$$|M|^2 = (4\pi)^3 \sum_{l=0}^{\infty} l \left[\left| \int_0^\infty f_i^{l-1}(r) f_f^l(r) dr \right|^2 + \left| \int_0^\infty f_f^{l-1}(r) f_i^l(r) dr \right|^2 \right]$$

- By carefully picking f^0 and f^1 (Ohmura and Ohmura, 1961) we can arrive at (Dalgarno and Lane, 1966)

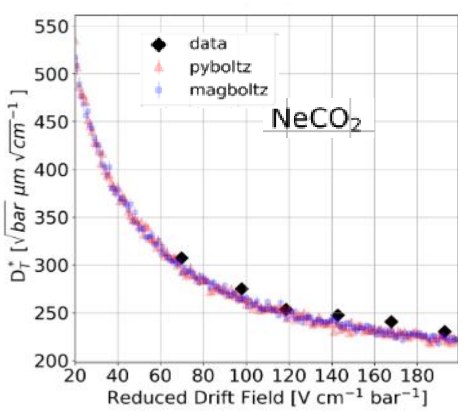
$$\frac{d\sigma}{d\nu} = \frac{8}{3}\frac{r_e}{c}\frac{1}{h\nu}\left(\frac{\varepsilon_i - h\nu}{\varepsilon_i}\right)^{1/2} \cdot \left[\varepsilon_i \cdot Q_{(m)}(\varepsilon_i - h\nu) + (\varepsilon_i - h\nu) \cdot Q_{(m)}(\varepsilon_i)\right]$$

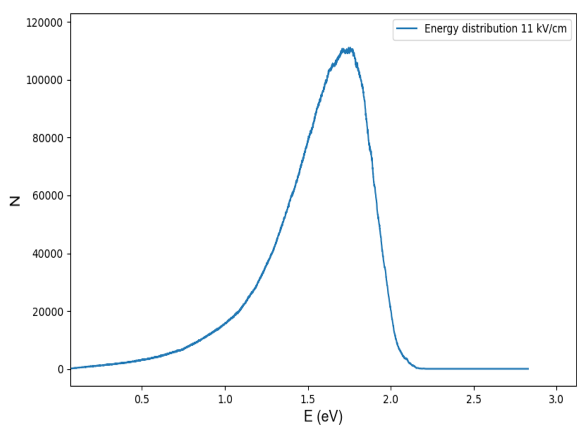
Computing neutral bremsstrahlung

- Once this is calculated, we can directly calculate the NBRS emission

$$Y \equiv \frac{dN_\gamma}{dz} = \frac{1}{v_d}\int_0^\infty \frac{dN_\gamma}{d\nu dt} = \frac{1}{v_d}\int_0^\infty \int_0^\infty N\frac{d\sigma}{d\nu}v(\varepsilon)\frac{dP}{d\varepsilon}d\varepsilon d\nu$$

- For this we still need the energy distribution and the drift velocity, which we can get from PyBoltz, a MC electron transport code



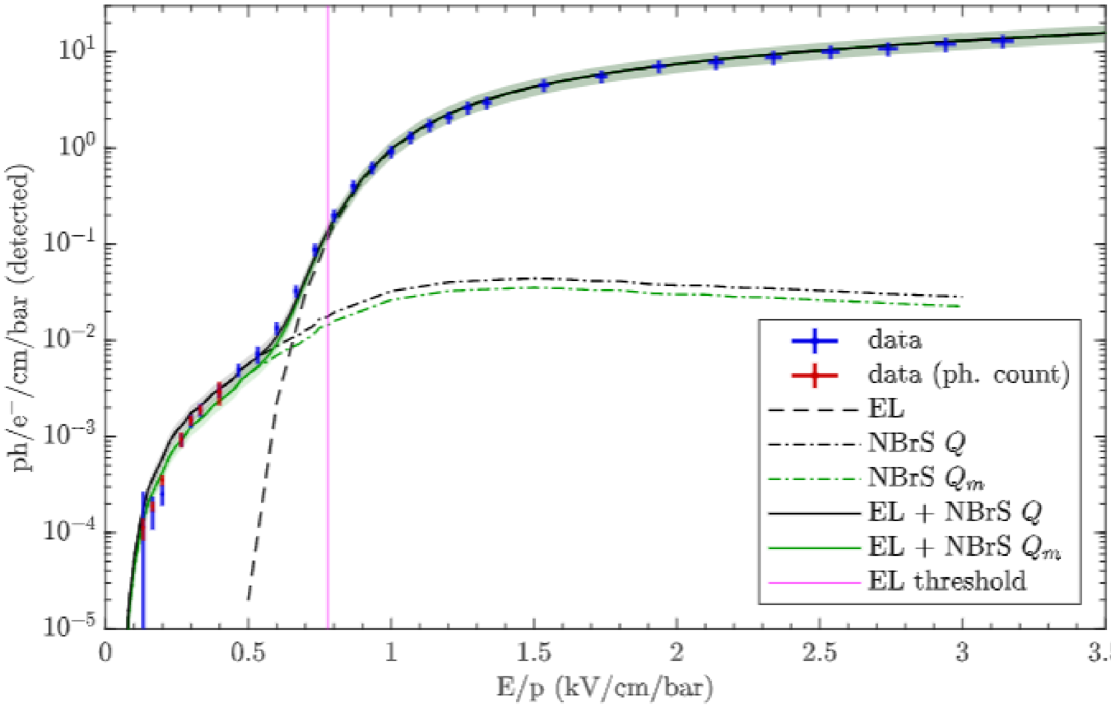


- In order to compare with the detected results we need to correct for the geometrical efficiency and the quantum efficiency

arXiv:1910.06983

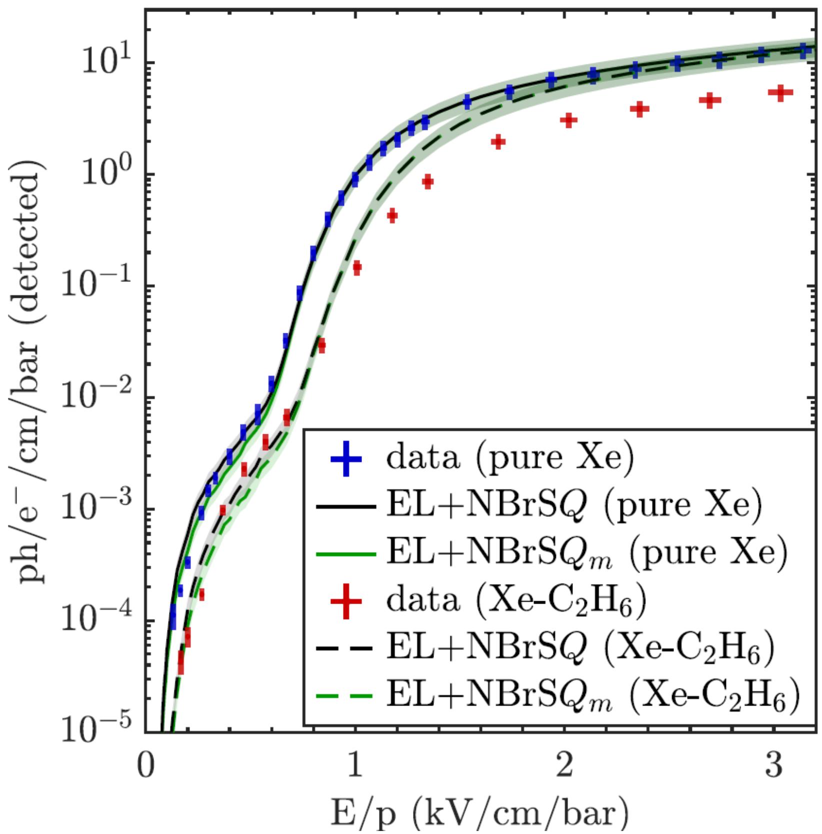
Comparison with experimental results

- The experimental results for Xe and the simulations match quite well



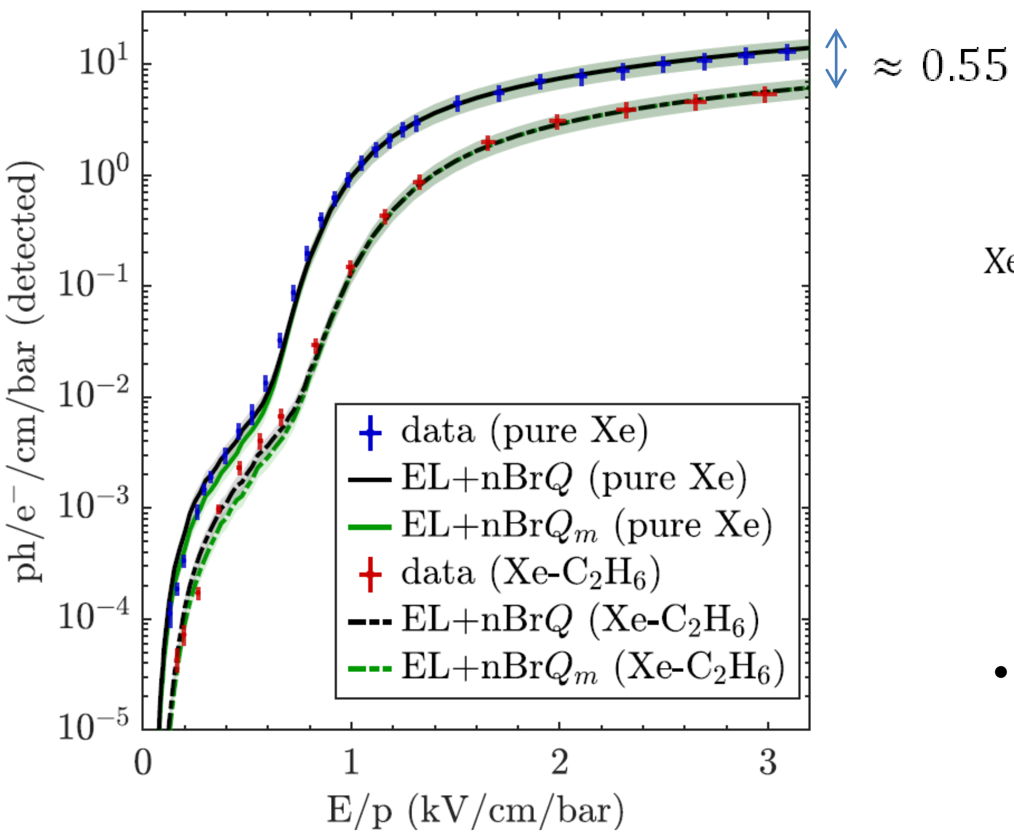
Comparison with experimental results

- Xe-C_2H_6 measurements at 0.12% molar concentrations were also performed



Comparison with experimental results

- Xe-C_2H_6 measurements at 0.12% molar concentrations were also performed
- Once quenching is added simulation matches the data quite well



- Simplified quenching scheme

$$\mathrm{Xe_2^*} \begin{cases} \mathrm{Xe_2^*} \rightarrow \mathrm{2Xe} + h\nu \\ \mathrm{Xe_2^*} + \mathrm{C_2H_6} \rightarrow \mathrm{2Xe} + \mathrm{C_2H_6^*} \end{cases}$$

$$P_Q = \frac{K}{K + \frac{1}{\tau}} \qquad P_{scin} = \frac{1/\tau}{K + \frac{1}{\tau}}$$

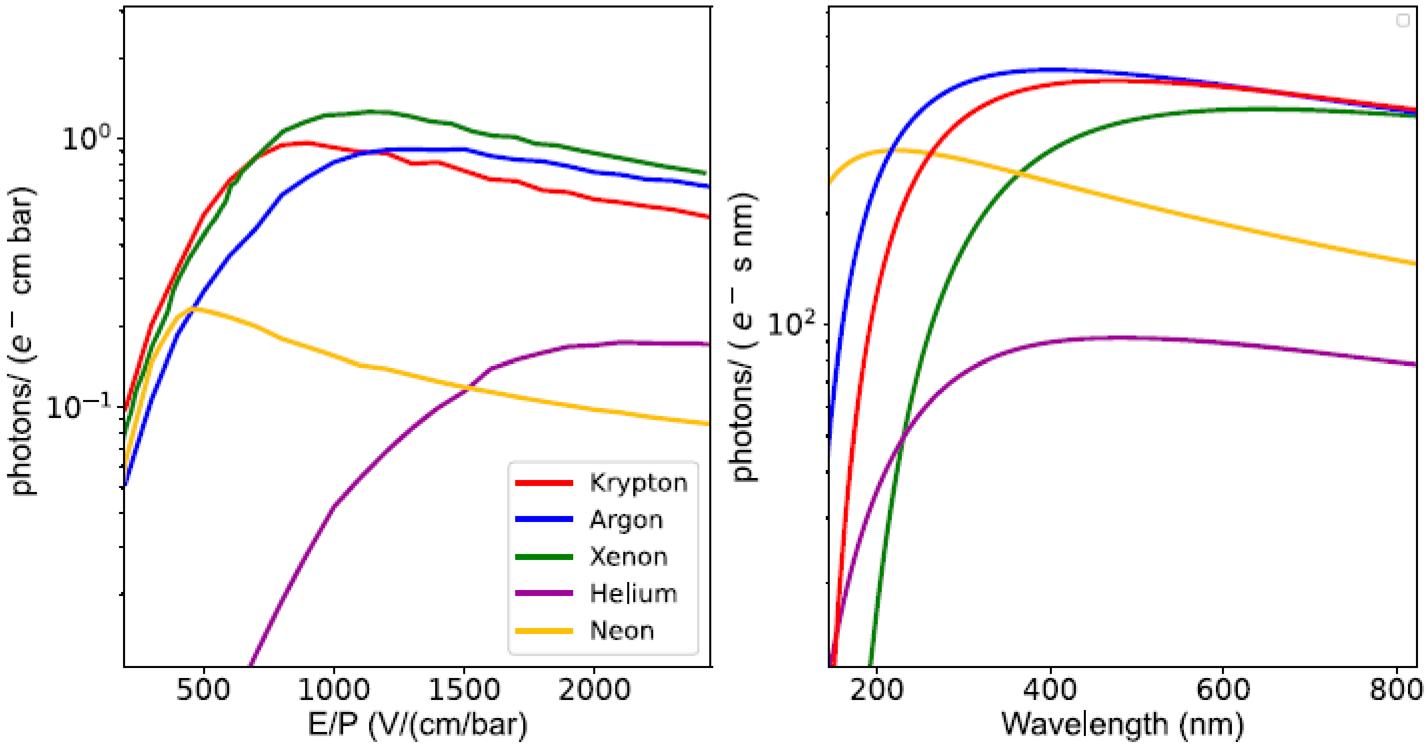
- Expected probability in this model

$$P_{scin} = 0.37$$

K values from Setser et al, 1978
https://doi.org/10.1063/1.436447

Simulations for pure noble gases

- These simulations can be run for other gases

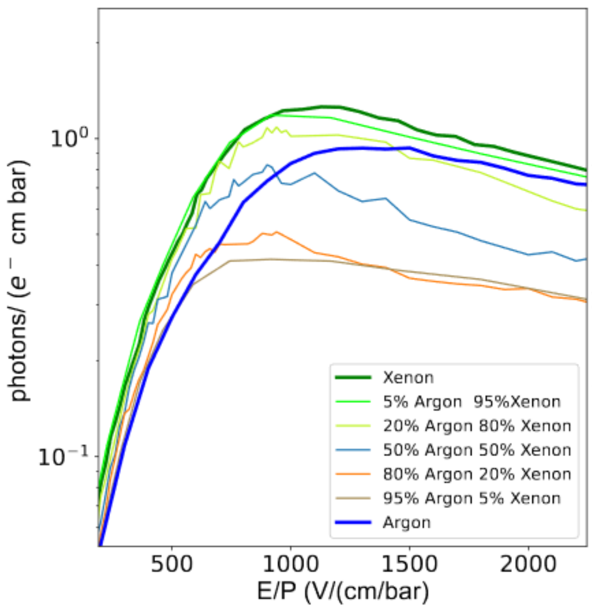


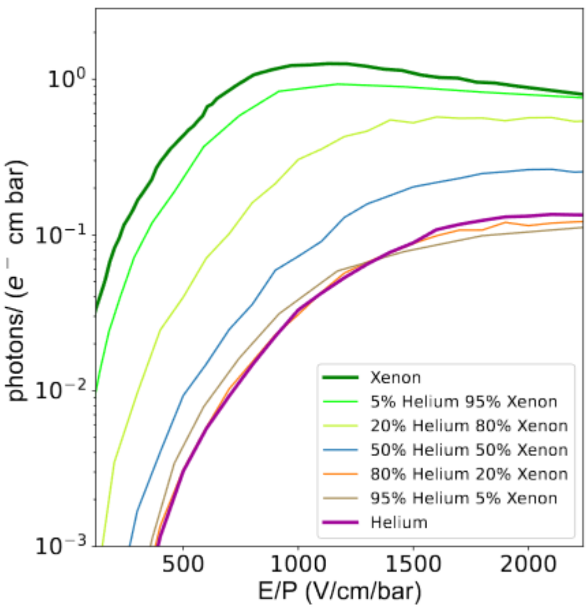
Simulations for noble mixtures

- This framework is valid when inelastic reactions are not dominant, so mixtures of either pure noble gases or weakly quenched gases

$$Yield_{AB}\left(\frac{dP}{dE_{AB}},\sigma_A+\sigma_B\right)=\left(\frac{A}{A+B}\right)Yield_A\left(\frac{dP}{dE_{AB}},\sigma_A\right)+\left(\frac{B}{A+B}\right)Yield_B\left(\frac{dP}{dE_{AB}},\sigma_B\right)$$

- This effect can be tuned with different mixtures

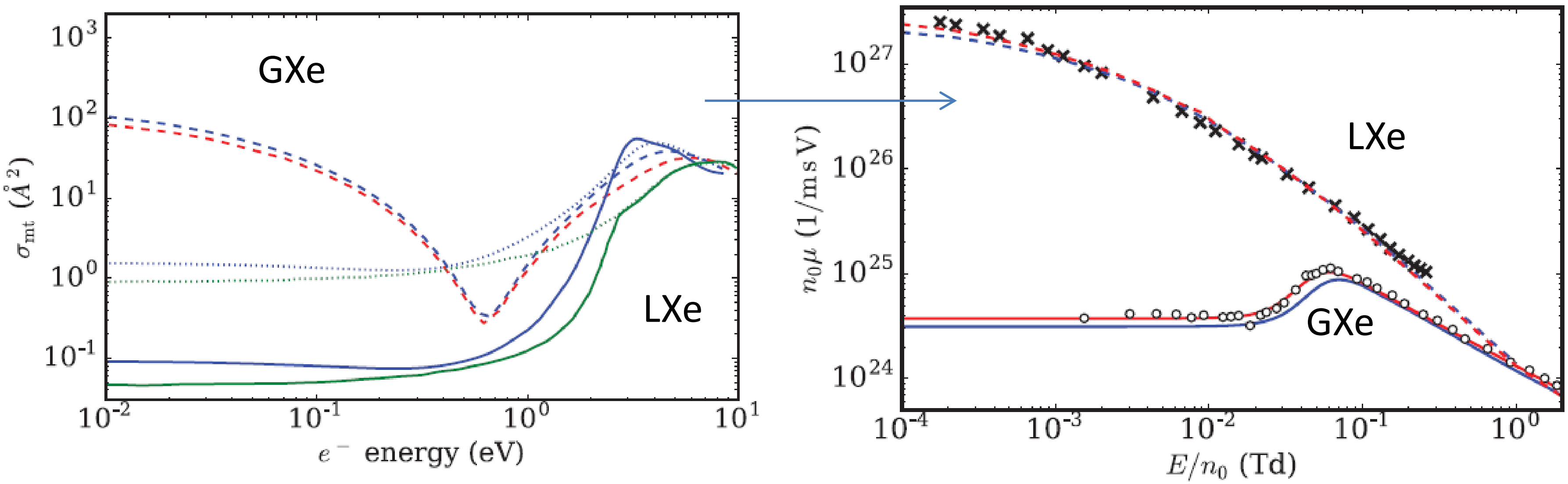




Liquid elements

- Given there are multiple TPCs with noble elements in liquid phase we aimed at predicting NBRS in the liquid

- For that we need a cross section for the liquid



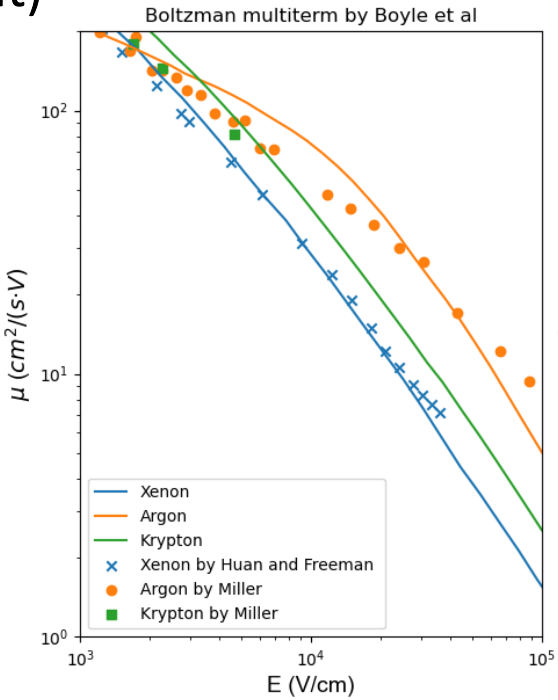
- First principles calculations that reproduce measured data for gas and liquid

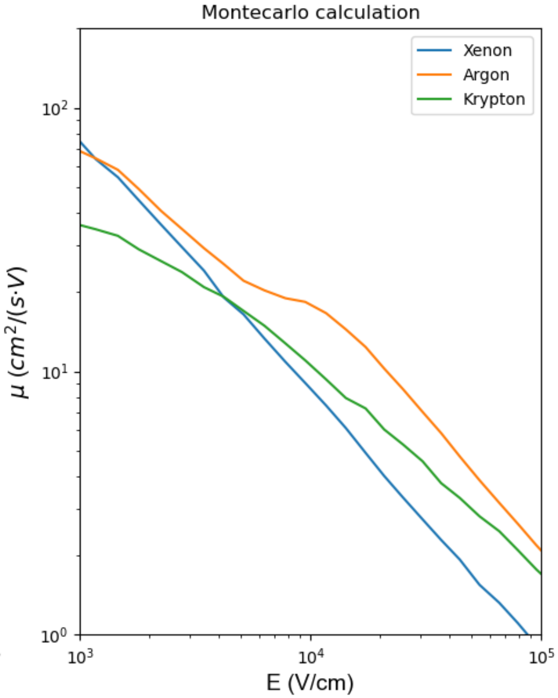
G. J. Boyle et al, 2015 (The Journal of Chemical Physics), 2016 (Journal of Physics D: Applied Physics), 2018 (Plasma Sources Science and Technology)

Liquid elements

- The liquids are implemented as dense gases with the liquid momentum transfer cross section in PyBoltz's MC code

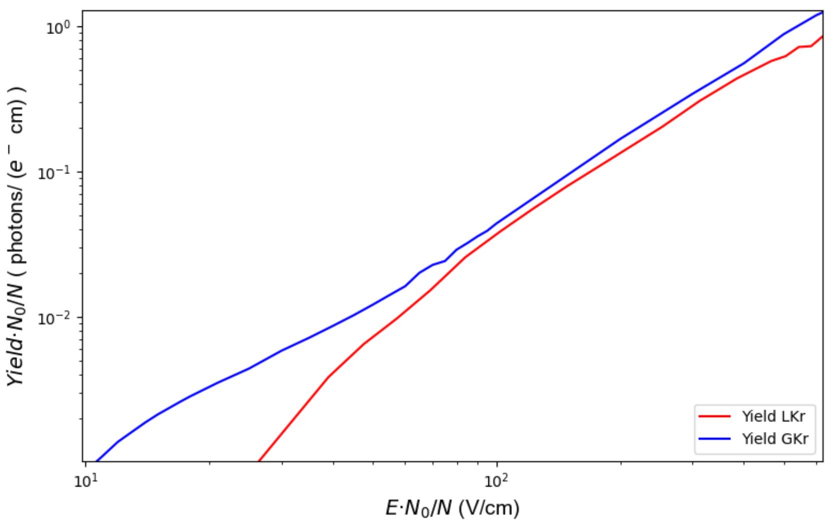
- This doesn't take into account medium effects at low energies (yet, working on it)

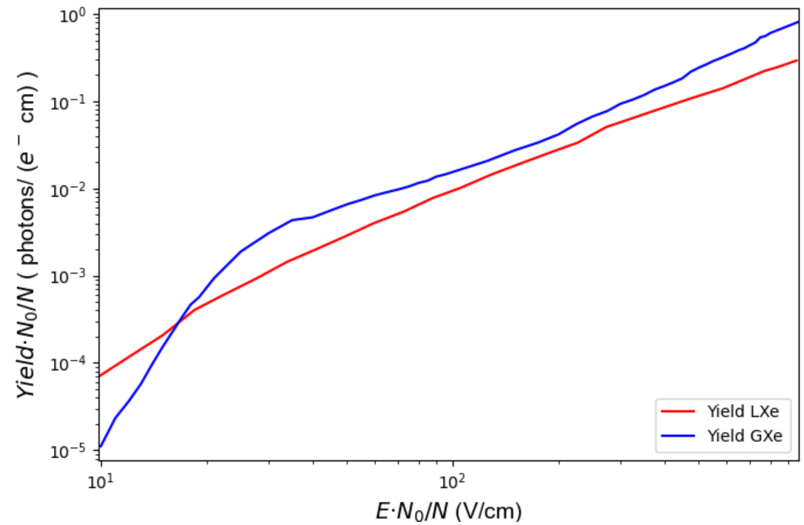


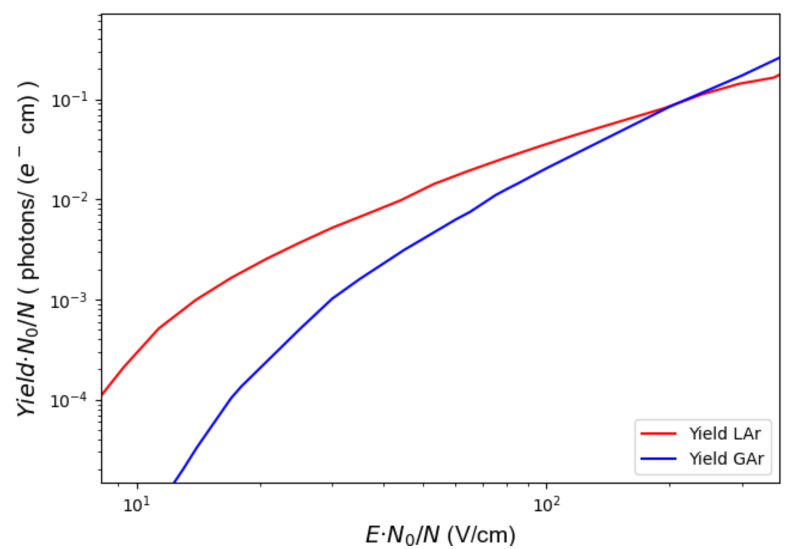


Comparison liquid-gas

- Results for liquid phase and gaseous phase of noble elements



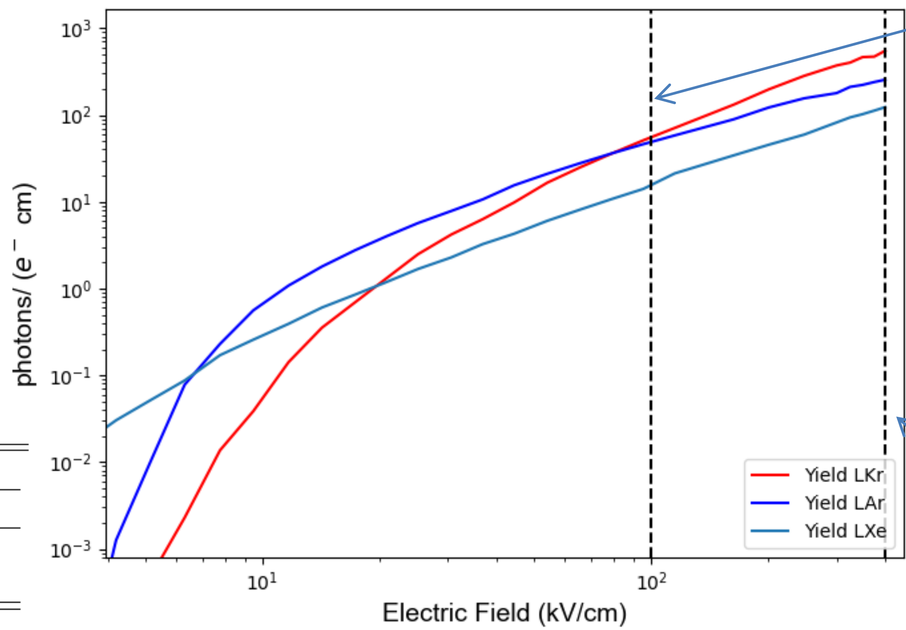




N0=nº of molecules/volume
for gas phase

Simulation of liquid elements

- Yields are significant at high fields



LAr breakdown voltage for 1 cm gap
F. Bay et al, ETH Zurich, 2014

LXe breakdown voltage from S.E. Derenzo et al Phys. Rev. A 9 (6) (1974) 2582

region	size (cm)	ph/e^{-1}
NEXT-White		
drift	53	3.08
buffer	12.9	7.87
LZ		
region	size (cm)	ph/e^{-1}
drift	145.6	-
reverse field	13.75	0.17-1.13
skin field	8	0.41-2.56
n-EXO		
region	size (cm)	ph/e^{-1}
drift	125	-
buffer	5	1.60

Carlos A. O. Henriques, P. Amedo et al. Submitted to PRX

Conclusions and future plans

Conclusions

- The experimental results for GXe and simulations are in good agreement, pointing to NBS as the source of light at E/p below EL threshold
- Simulations for mixed noble gases (as well as weakly quenched mixtures) predict enhancement or suppression based on the mixture
- Simulations in liquid predict significant yield at high fields

Soon to be uploaded to GitHub!

Back up slides

Theory of NBS

-Assume an electron with energy Eb, momentum kb and wavefunction ϕb(r) undergoes a transition to a new state ϕa(r) with energy Ea and momentum ka

$$h\nu = E_b - E_a = \frac{\hbar}{2m}(k_b^2 - k_a^2)$$

-Energy radiated by unit of frequency and emission cross section

$$\frac{d\sigma_{nu}}{d\nu} = \frac{1}{\nu\nu}\frac{dS_\nu}{d(h\nu)} = \frac{8\pi e^2 \nu^3 k_b m^2}{3\hbar^3 c^3 k_a}|M|^2 \quad \text{with} \quad M =< \phi_a|r|\phi_b >$$

-To calculate M, we would need to perform the integrals over the wavefunctions

$$|M|^2 = (4\pi)^3 \sum_{l=0}^{\infty} l \left[\left| \int_0^\infty f_b^{l-1}(r) f_a^l(r) dr \right|^2 + \left| \int_0^\infty f_a^{l-1}(r) f_b^l(r) dr \right|^2 \right]$$

-Instead, we can resort to the partial waves method and use some approximations to avoid doing that

$$f(\theta) = \sum_{l=0}^{\infty} (2l+1) a_l(k) P_l(\cos\theta)$$

Theory of NBS

-If we stay at low energies, we don't need to consider partial waves above the incident S wave and the scattered P wave (l=0 and l=1)

-All but the functions f0 and f1 in the integral can be ignored and those two can be replaced

$$f^{0} = k^{-1}\sin(kr + \eta_0)$$

$$f^{-1} = k^{-1}\left(\frac{\sin kr}{kr} - \cos kr\right)$$

$$\longrightarrow \quad M^{\pm}(0, k_b^2 | 1, k_a^2) = \frac{1}{2} k_a sin\delta_0$$

-This allows us to quickly compute M

$$|M|^2 = \frac{64\pi^2}{k_b^2 - k_a^2}[k_a^2 q_0(E_b) + k_b^2 q_0(E_a)] \qquad q_{0(E)} = \frac{4\pi}{k^2}\sin^2\eta_0(k)$$

-And produce a final result

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

Comparison with experimental results

- Xe-C2H6 measurements at 0.12% molar concentrations were also performed
- A shift in the electrical field to compensate the cooling of the electrons doesn't recover the EL values