Fundamental Properties of Noble Liquids

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CPAD Workshop
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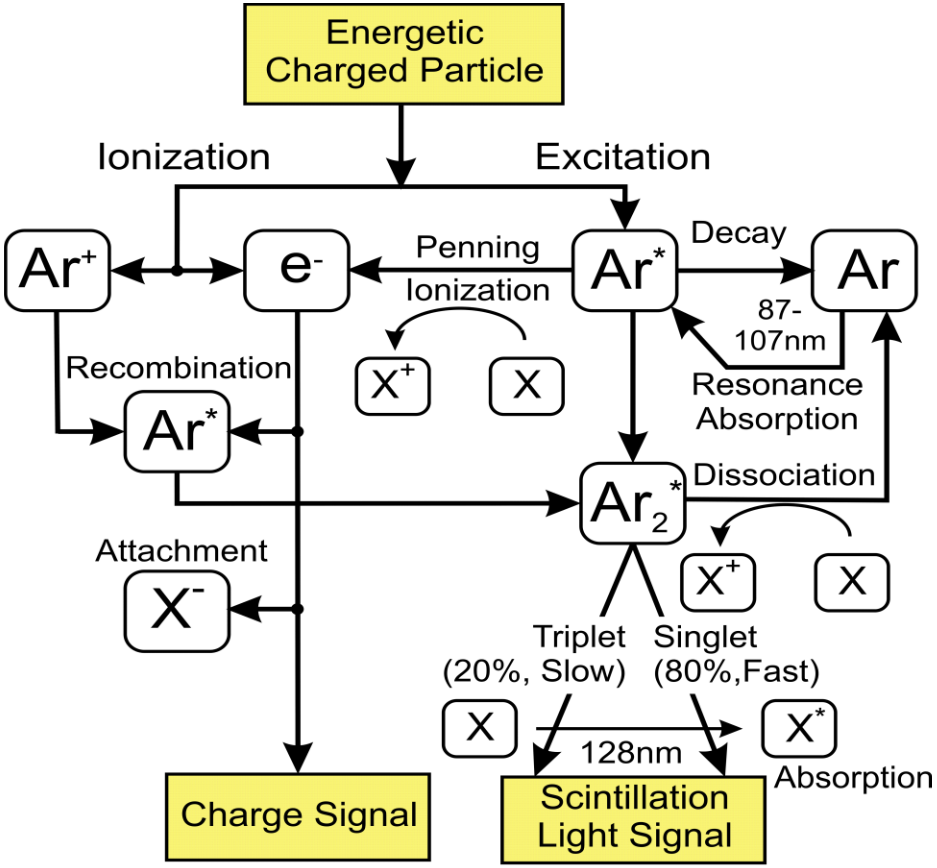
What Happens When Charged Particles Lose Energy in LAr?



Energetic Charged Particle

Ionization

Excitation

Ar^+

e^-

Penning Ionization

Ar^*

Decay

Ar

87-107nm

Resonance Absorption

X^+

X

Recombination

Ar^*

Dissociation

Ar_2^*

X^+

X

Attachment

X^-

Triplet (20%, Slow)

Singlet (80%,Fast)

X

128nm

X^*

Absorption

Charge Signal

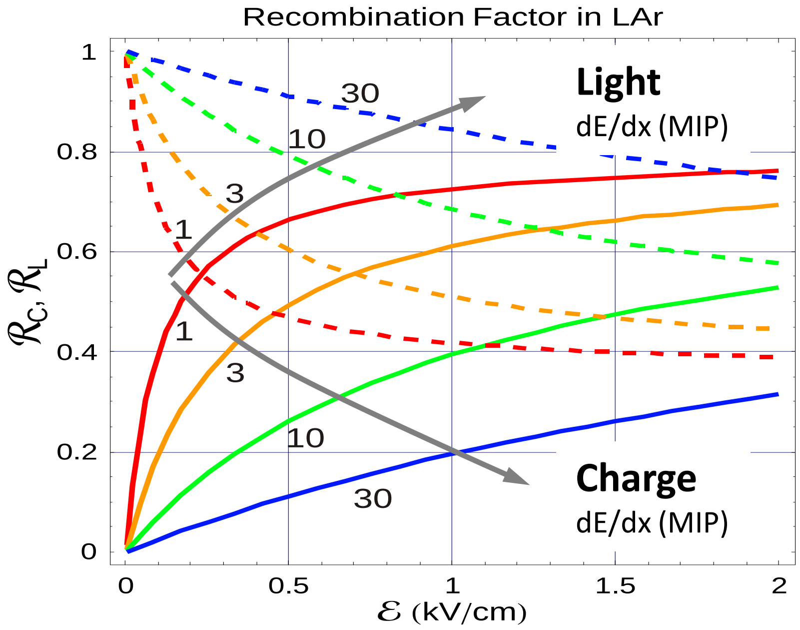
Scintillation Light Signal

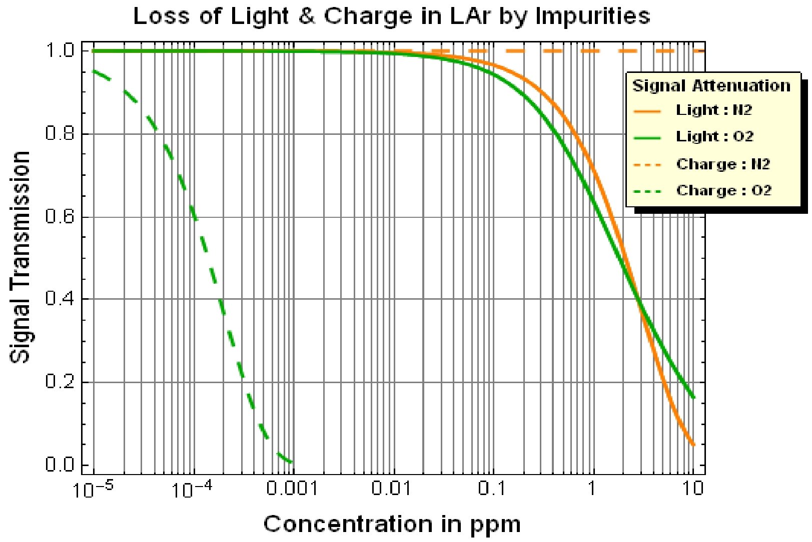
42,000 per MeV

8980 e/mm for MIP
(maximum)

51,000 per MeV

10,900 ph/mm for MIP
(maximum)
cf. 40,000 for NaI(Tl)





Charge response to ionization and the transport of charge

Observation of the motion of electrons in noble liquids is the primary means of event tracking and calorimetry in TPCs. All of the processes that contribute to the production and transport of electrons and ions are of interest for the optimization of TPCs.

1. Specific ionization as a function of specific energy loss and electric field *especially at high energy loss* (the recombination factor)
2. Diffusion of electrons (transverse & longitudinal) as a function of electric field
3. Attachment cross sections (rate constants) of electrons for all impurities
4. Mobility of positive ions (including the ions of impurities)
5. Optimization of transport properties with dopants, as has been done for gaseous detectors
6. Development of structures and conditions for gain in noble liquids
7. Optimization of photocathodes as a high brightness source of electrons in noble liquids
8. Analysis through Monte-Carlo simulations of optimization of signal processing and detector performance.
9. Henry's law constants for common impurities

Optical response to ionization and the transport of light

Development of optical detection of the scintillation (and Cerenkov) light produced by ionizing radiation in noble liquids, using photomultipliers and avalanche diodes or other solid state devices, with or without wavelength shifters and light pipes. This detection is useful for marking the start of electron drift for TPC z coordinate measurement, for particle identification, and for background rejection. In particular, the ratio between the fast and the slow component of the VUV scintillation light is strongly dependent on the ionization density and can be used as a discriminating variable in dark-matter searches.

1. Specific scintillation as a function of specific energy loss, electric field, and impurities, especially *at high energy loss,* for both scintillation components.
2. Absorption of scintillation light by impurities
3. Rayleigh scattering of scintillation light
4. Monte-Carlo simulation of optical response of detectors
5. Wavelength shifter coatings and dopants
6. Solid state detectors in cryogenic liquids

Program beginning at CSU to measure opticlcal properties

LAr Detector R&D/Prototyping in US

- LAPD + LongBo
  - 35t LAr + ~2m drift stack
  - Few channels of BNL FE ASIC
  - Operation CY14?
- MicroBooNE
  - 170t LAr + 2.5m drift
  - ~8000 channels of BNL FE ASIC
  - Operation mid CY2014
- LANL LDRD LArTPC
  - ~1/3 MicroBooNE, 1m drift?
  - Duplicates ~2000 channels of MicroBooNE
  - Construction CY13, 14
- ArgoNeuT
  - ~0.2t + 0.5m drift
  - Few channels of BNL FE ASIC
  - Operation completed in CY13
- FNAL LARiAT
  - ~Size of MicroBooNE
  - BNL FE & ADC ASICs???
  - Construction CY14, operation CY15?
- LBNE 35t
  - 35t LAr + 3 small APAs (~3000 channels)
  - ~3000 channels, BNL FE + ADC + FPGA
  - Cryostat ~complete; operation mid CY14

The recombination factor, particularly at high *dE/dx, is not well measured.*

Precise knowledge of this is necessary for accurate PID and Calorimetric Reconstruction!

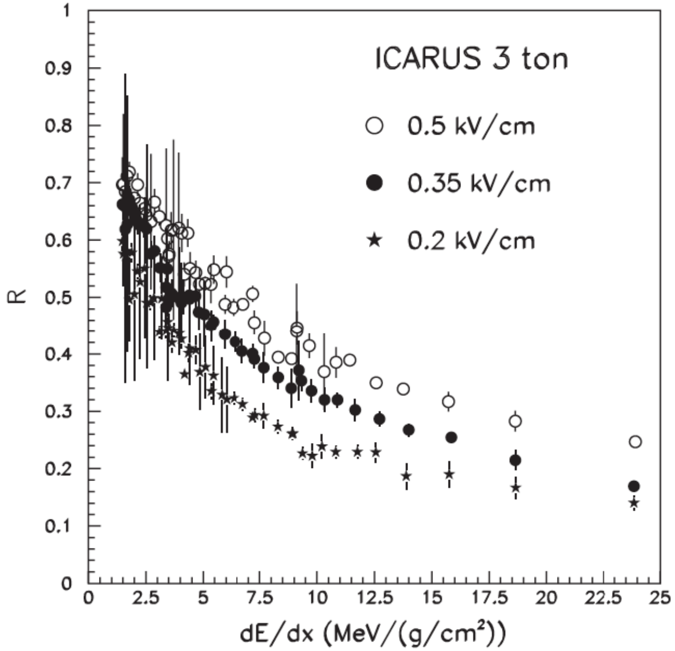


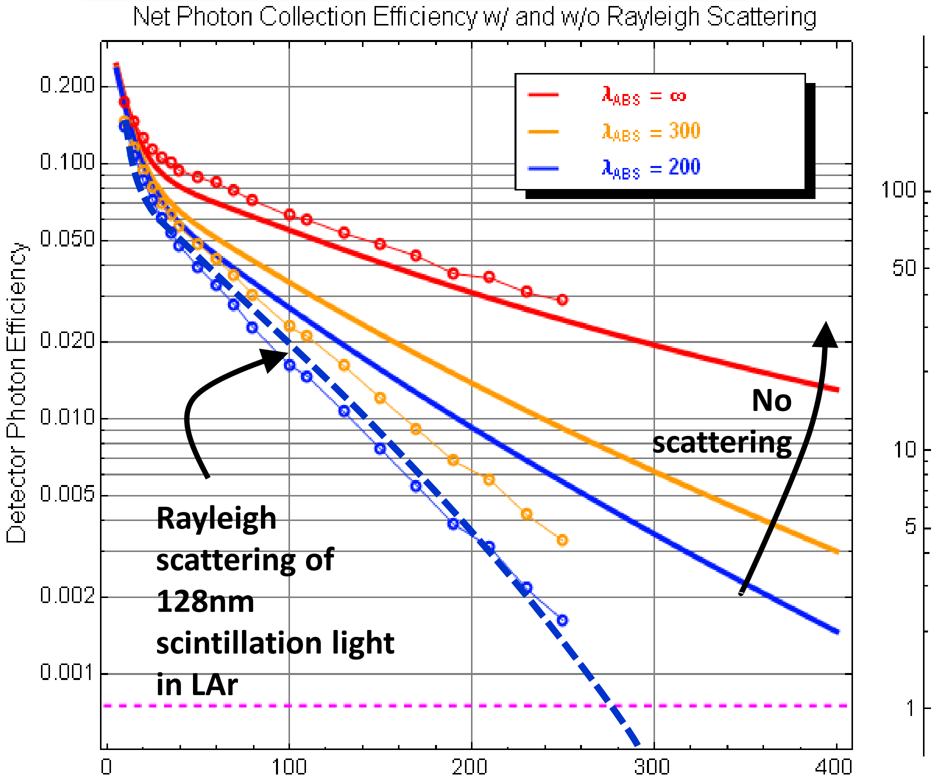
Fig. 1. Recombination factors measured with the 3 ton ICARUS prototype as a function of the theoretical particle stopping power, for different electric field values.

Data from ICARUS for CR μ and p from Flavio Cavanna

Selected Properties of LAr

Transport properties: scintillation light absorption and electron diffusion

Light propagation in LAr

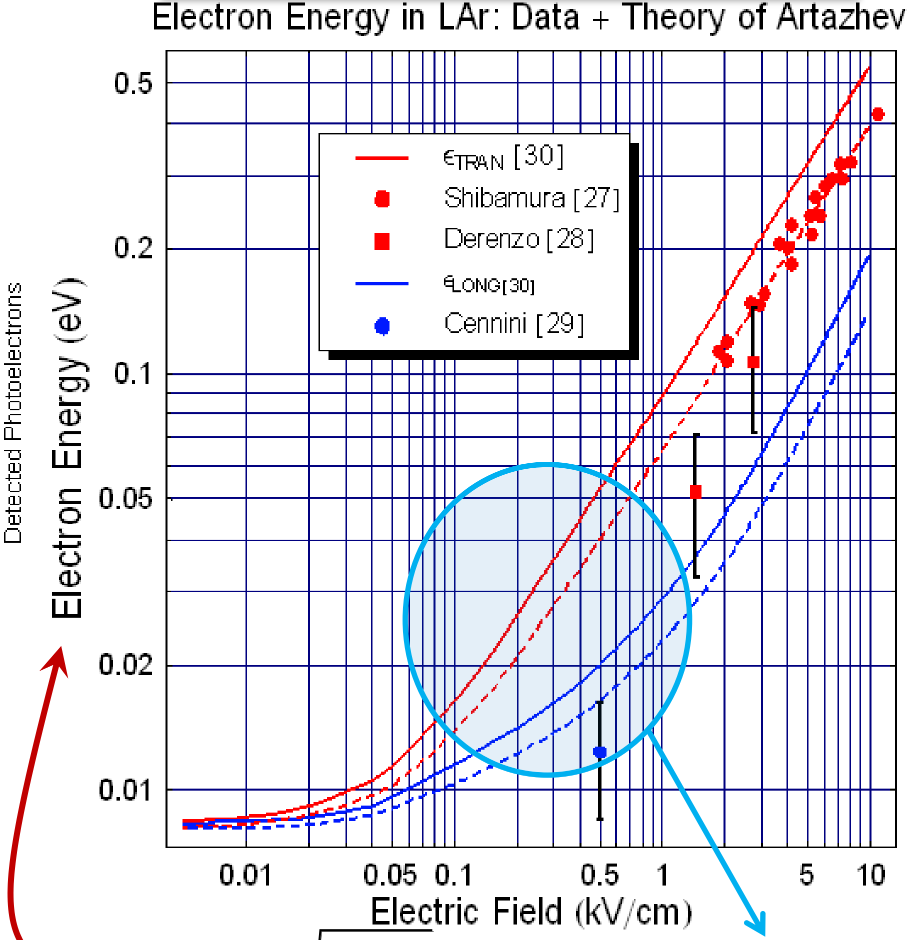


No scattering

Rayleigh scattering of 128nm scintillation light in LAr

Liquid	Wavelength	Scattering Length (m)		Absorption Length (m)
	(nm)	Calculated	Measured	Deduced
Neon	80	60	-	-
Argon	128	95	66	200
Krypton	147	60	82	negative!
Xenon	174	30	29	>800

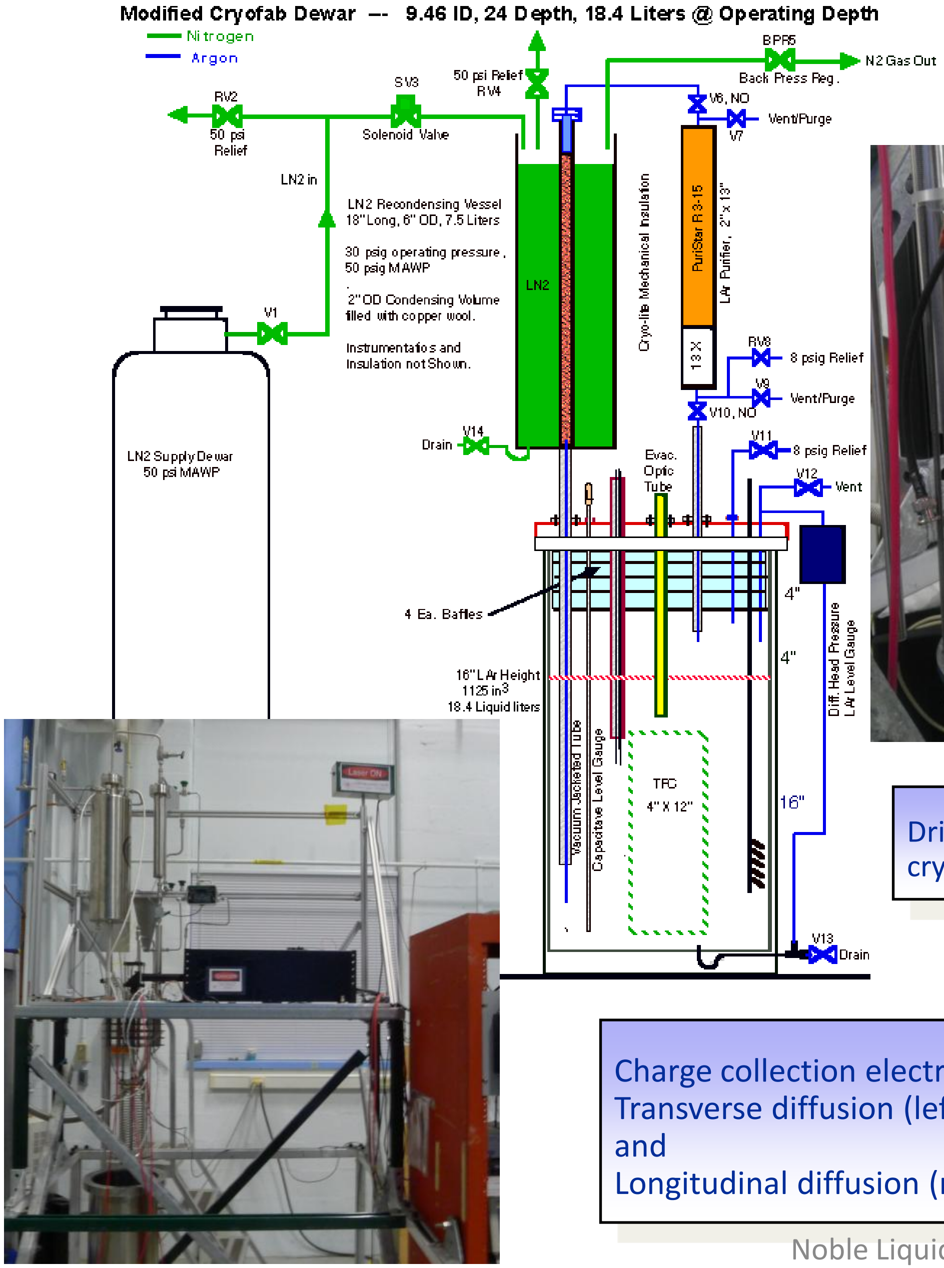
Electron diffusion in LAr



~no data below 1.5 kV/cm

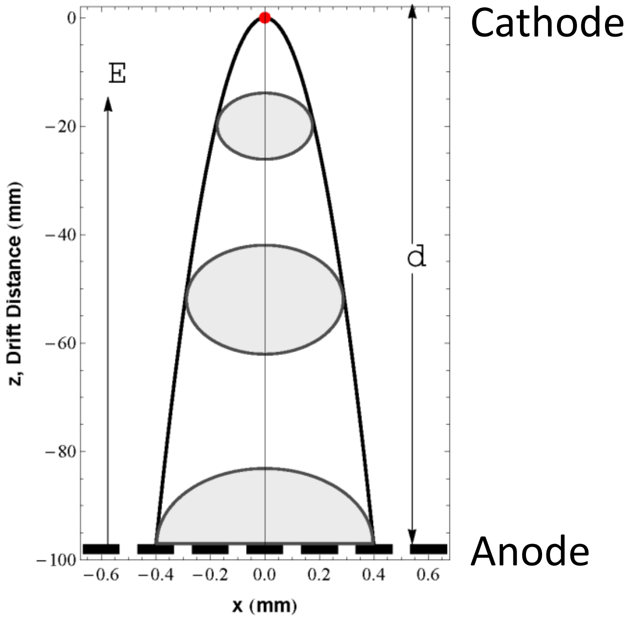
$$\varepsilon_e \equiv \frac{eD_e}{\mu_e}; \quad \sigma = \sqrt{\frac{2\varepsilon_e \Delta z}{E_D}}$$

Electron Drift and Diffusion in LAr

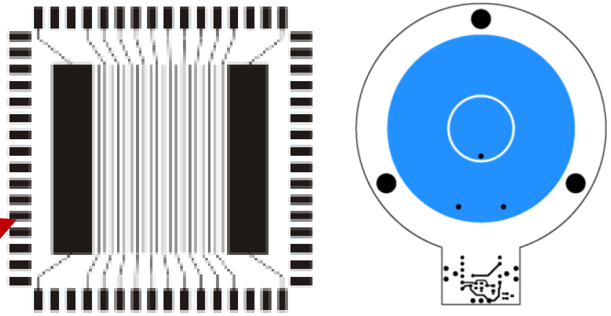


$$\varepsilon_e \equiv \frac{eD_e}{\mu_e}$$

$$\sigma = \sqrt{\frac{2\,D\,z}{\mathrm{v}}} = \sqrt{\frac{2\,\varepsilon\,z}{\mathrm{E}}}$$



Drift stack above cryostat



Charge collection electrodes for Transverse diffusion (left) and Longitudinal diffusion (right)

Rayleigh Scattering as an Isotopic Random Walk

For an isotropic random walk in *d*-dimensional space with an rms step size of $<r^2>$, after *N* steps the PDF of the distance from the origin approaches[1]

$$P_N(R) \sim S(d) R^d \frac{Exp[-dR^2/(2\langle r^2\rangle N)]}{(2\pi\langle r^2\rangle N/d)^{d/2}} \quad as\, N \to \infty$$

S(d) is the area of a d-sphere

For Rayleigh scattering, the steps are exponentially distributed, and the rms step size is

$$\langle r^2\rangle^{1/2} = \left(\int_0^\infty r^2 Exp[-r/\lambda_R]\mathrm{d}r) / \int_0^\infty Exp[-r/\lambda_R]\mathrm{d}r\right)^{1/2} = \sqrt{2}\lambda_R$$

In three dimensions, the mean distance from the origin is

$$\langle R\rangle = \frac{1}{2}\sqrt{3\pi N}\lambda_R$$

So the distance walked (path length) after N steps is

$$L = N\lambda_R = \frac{4\langle R\rangle^2}{3\pi\lambda_R} = (0.4244/\lambda_R)\langle R\rangle^2 \quad as\, N \to \infty$$

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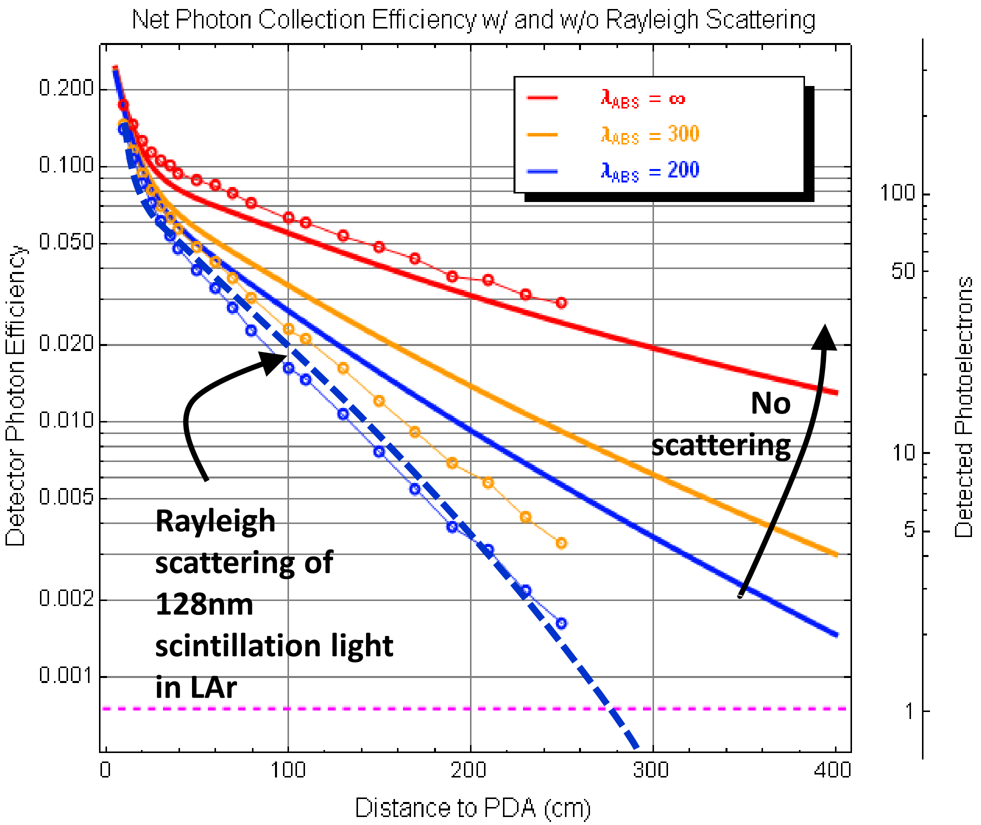
[1] B. Hughes, *Random Walks and Random Environments*, Vol I (Oxford,1995)

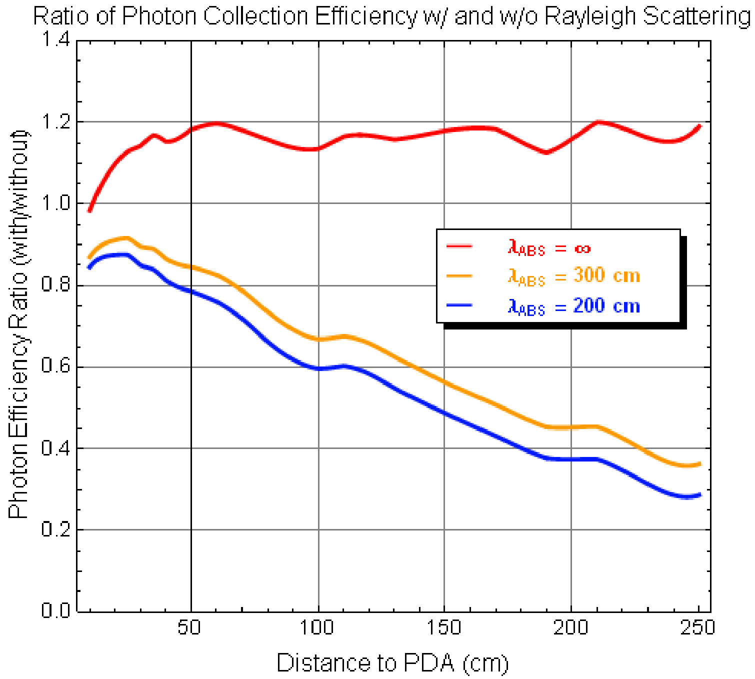
Monte Carlo Calculations with Rayleigh Scattering

Summary of Results for Collection Efficiency in X Direction
for three absorption lengths



Rayleigh scattering of 128nm scintillation light in LAr

No scattering



Smooth solid lines are numerical integration of solid angle times wire transmission times exponential absorption.

Points are Monte-Carlo calculation for 10,000 photons launched.

With Rayleigh scattering and absorption, the photon transport efficiency is much lower than without at distances greater than λ_R.

Electron Attachment aka Purity Requirements for LAr

$$q(y) = q(0)\, \mathrm{Exp}[-y/(v_D\, \tau)]$$

Electron Attachment Rates

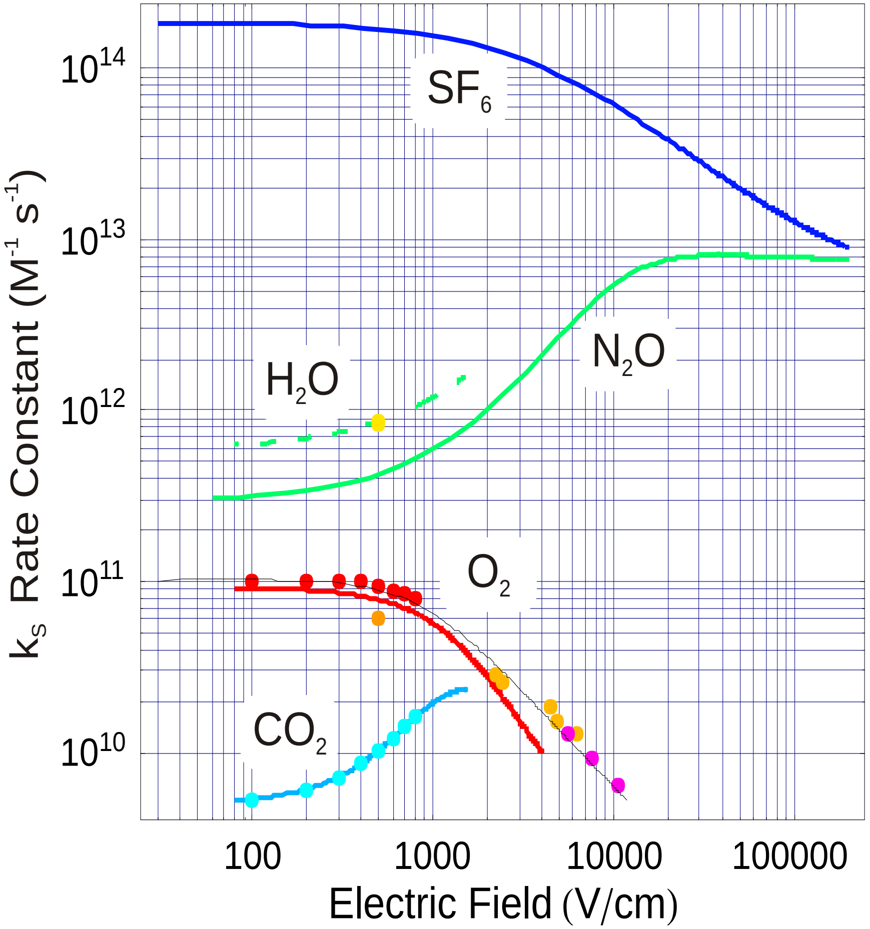
Reaction is $e + S \rightarrow S^-$
Rate is $dn_e/dt = k\, n_S\, n_e$

$\tau = (k_A\, n_S)^{-1}$
With $n_S = 3.49\times10^{-8}$ x ppb

at 500 V cm^{-1}
$v_D = 1600\ \mathrm{m\ s}^{-1}$
$k_A(O_2) = 8.1\times10^{10}\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$
$k_A(H_2O) = 8.6\times10^{11}\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$

$y_{mean}(O_2) = 0.57$/ppb (110 ppt for 5 m)
$y_{mean}(H_2O) = 0.053$/ppb (11 ppt for 5 m)

Electron Attachment Rate Constants in Ar

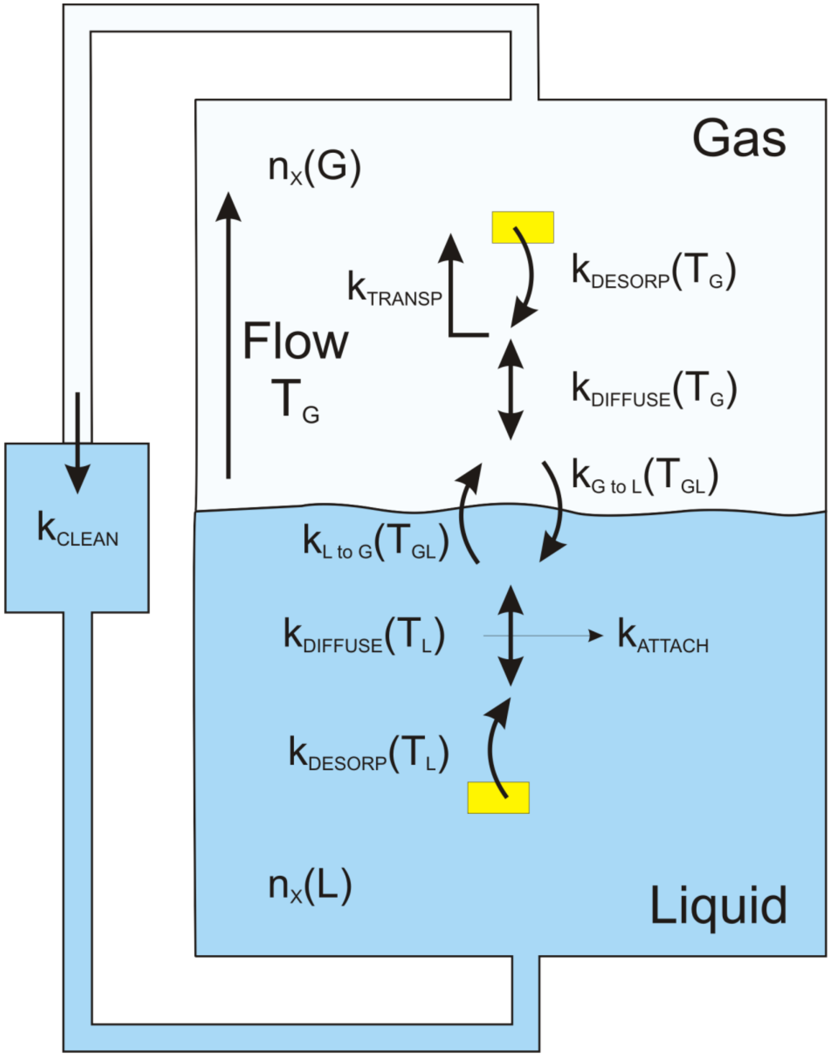


Need extremely high purity LAr to avoid charge attenuation along drift

See Andrews, et al., NIM A608 (2009) 251

Getting, and Keeping, High Purity Liquids

Impurity injection, transport, and removal



Rate constant for each process implies a differential equation

Solution of all eight coupled differential equations determines dynamic and steady-state impurity concentration in LAr

(Henry's Law}

$$k_H(T_{GL}) = \frac{k_{G\ to\ L}(T_{GL})}{k_{L\ to\ G}(T_{GL})}$$

At equilibrium, Henry's law determines impurity concentrations:
$x(liq) = k_{H,xx}\, x(gas)$
with **k_H =0.0041** for an ideal solute in Ar

Independent of where the solute is introduced (gas or liquid)

Not relevant for dynamic system.
For LAr cryostats, dominant process is $k_{DESORP}(T_G)$

Avoiding Contamination of Pure LAr

Water Desorption by FR4

$$k_D(T) = \mathrm{Exp}[-E_A/k(T-T_0)]$$

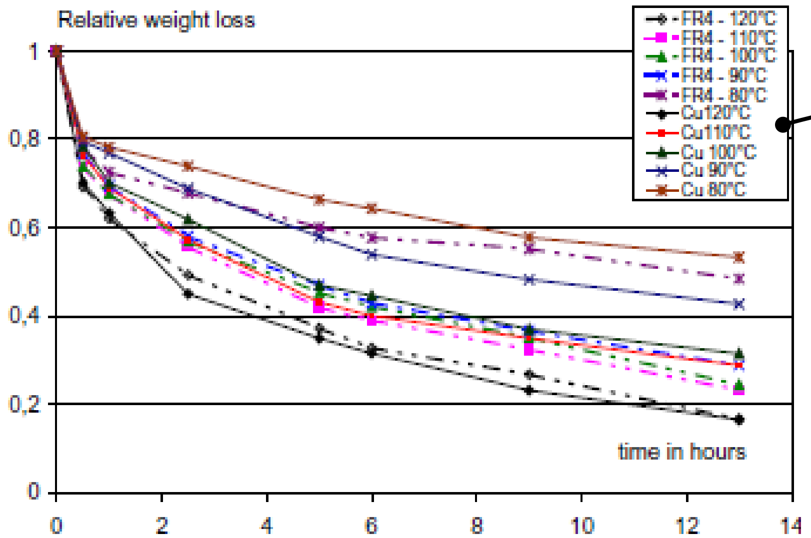
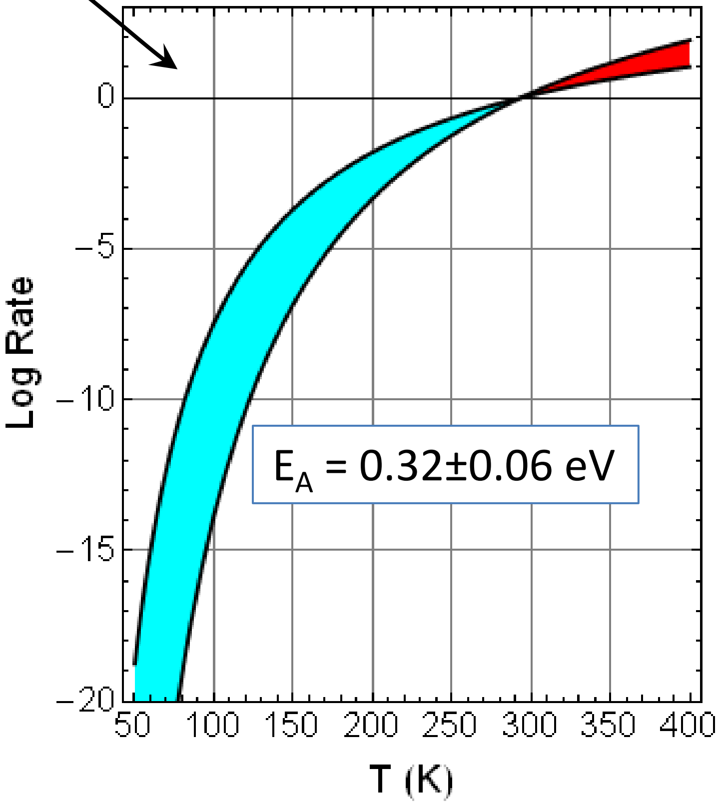


Fig. 3. Relative weight loss for 2 epoxy based PCBs at different temperatures.

K. Weide-Zaage et al., Microelectronics Reliability 45 (2005) 1662



Normalized Reaction Rate for Water Desorption by FR4

$E_A = 0.32 \pm 0.06$ eV

Desorption rate depends strongly on temperature

1. Keep sources of impurities in liquid or cold gas
2. Maintain large flow in gas to dominate diffusion

Lesson: In the liquid, don't care; in the gas, beware!

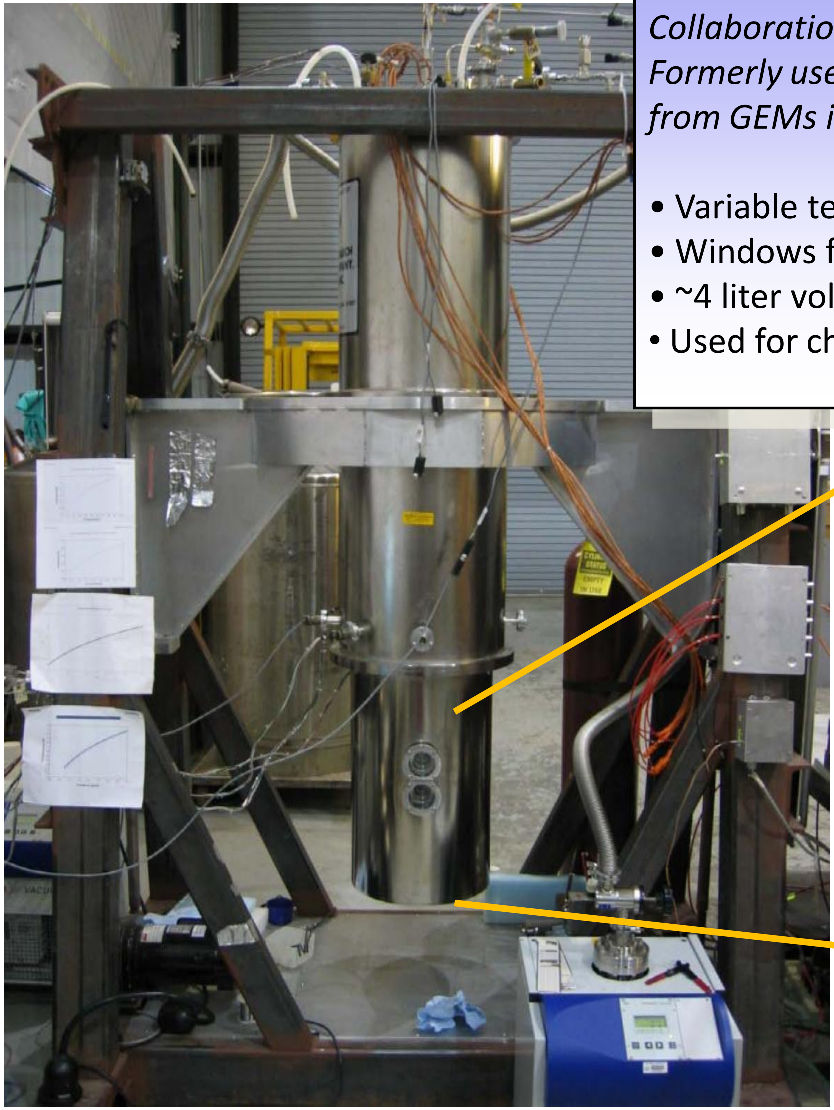
Charge and Light Production in Cold Supercritical Neon

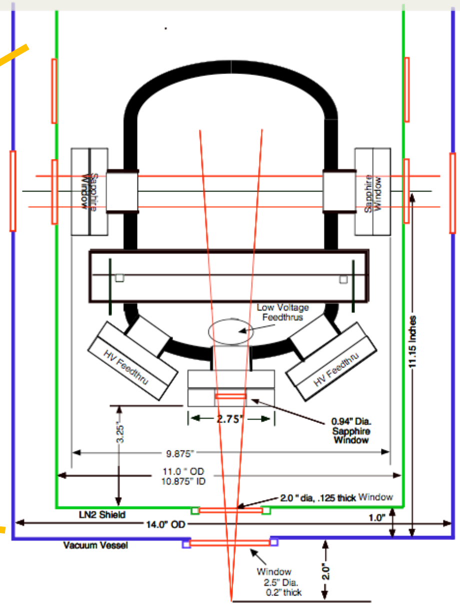
eBubble Cryostat

Collaboration with Columbia U.

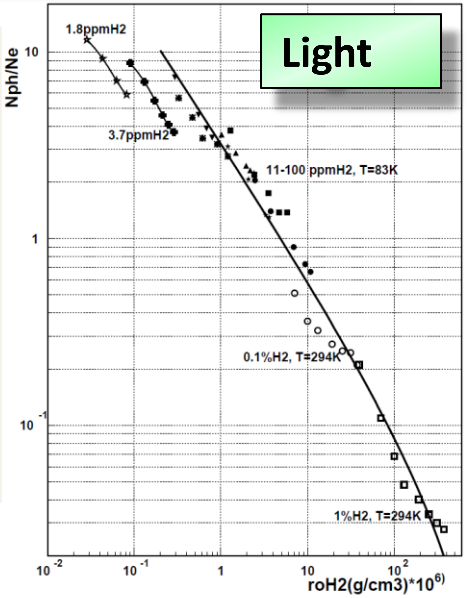
Formerly used for R&D on light production from GEMs in high density supercritical Ne

- Variable temp, high pressure cryostat
- Windows for optical measurements
- ~4 liter volume
- Used for charge and light measurements

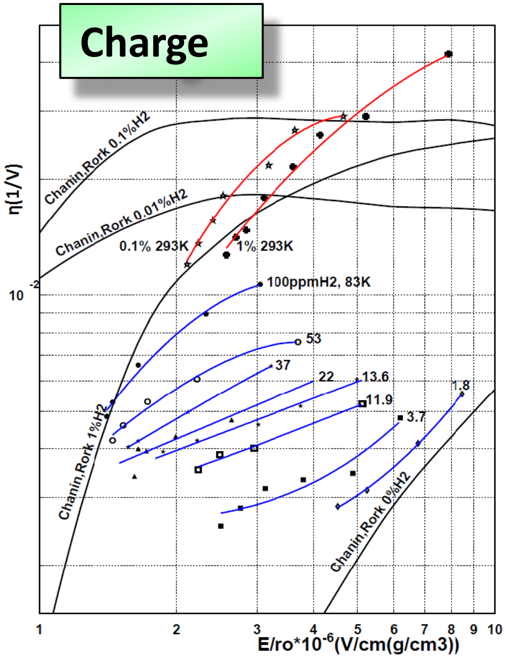




High Pressure Cryostat



Light

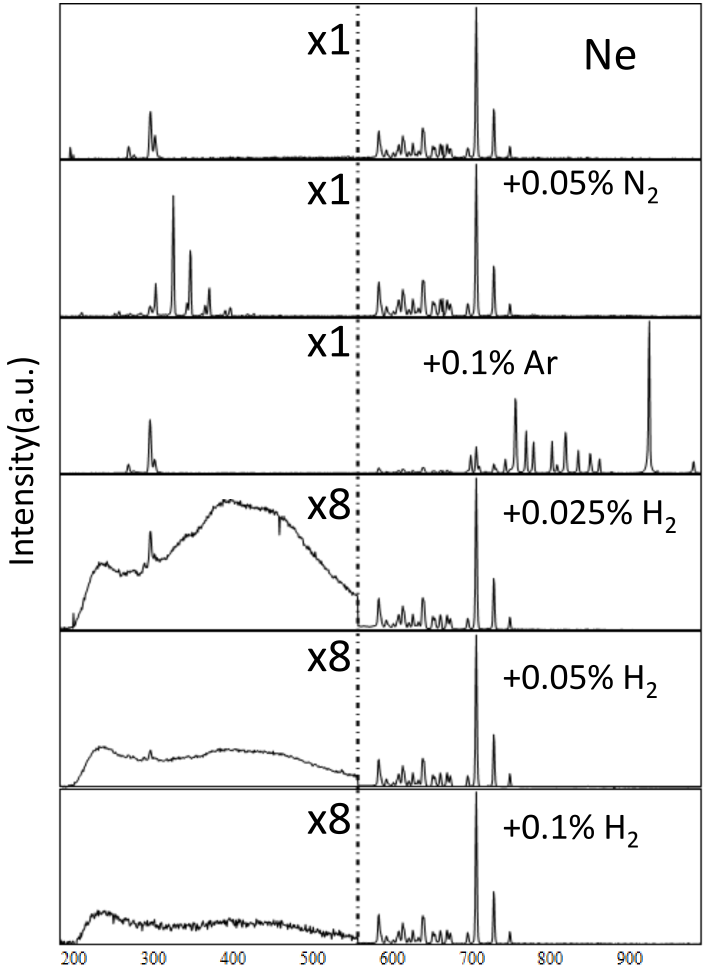


Charge

Optical Spectra of GEM Avalanches in Ne

At low H2 concentrations and high total pressure, a continuum emission extending into the UV dominated the optical content of GEM avalanches.

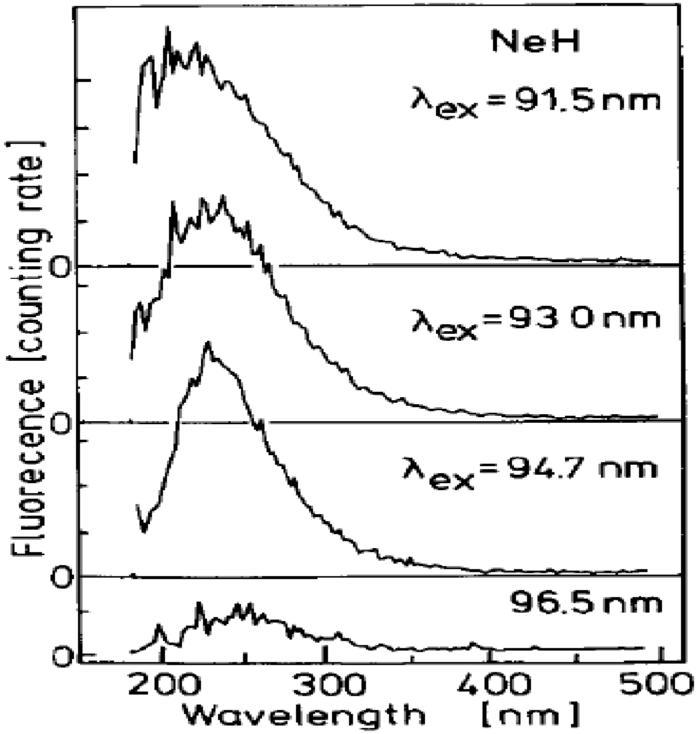
Measured Spectra for Gem Avalanches in NE + X



**The continuum part is magnified for visualization.*

The emitting is presumed to be NeH* produced in the Penning reaction

$$Ne^* + H_2 \rightarrow NeH^* + H^+ + e^-$$



Bound-free fluorescence of NeH as a function of excitation energy ***(from Thomas Mőller el at. Chem. Phys. Lett.136(1987)551)***

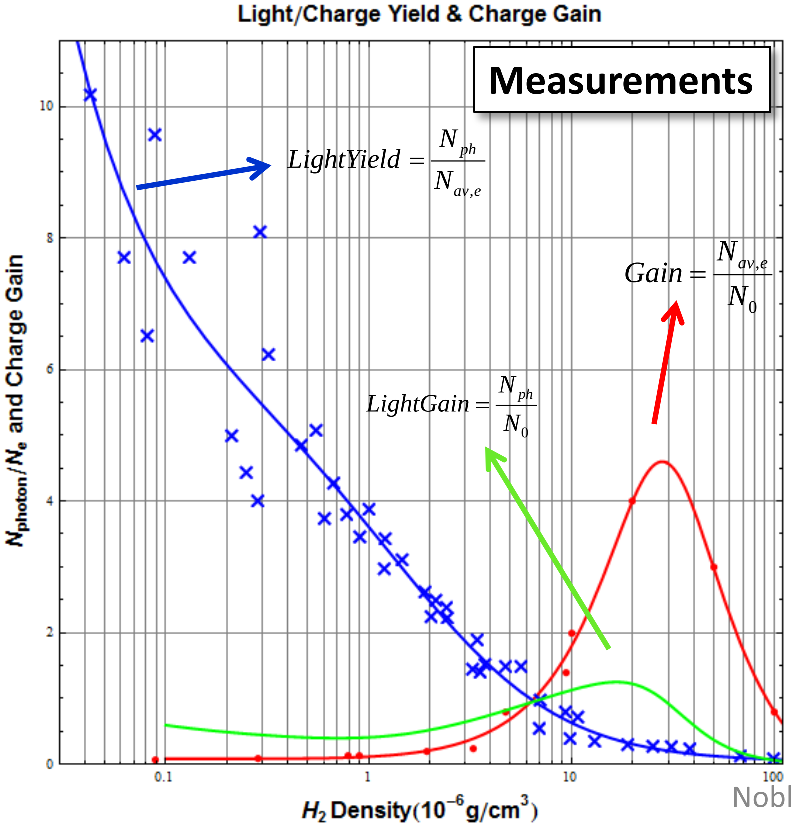
Light Gain in Ne+H2 and Model Predictions

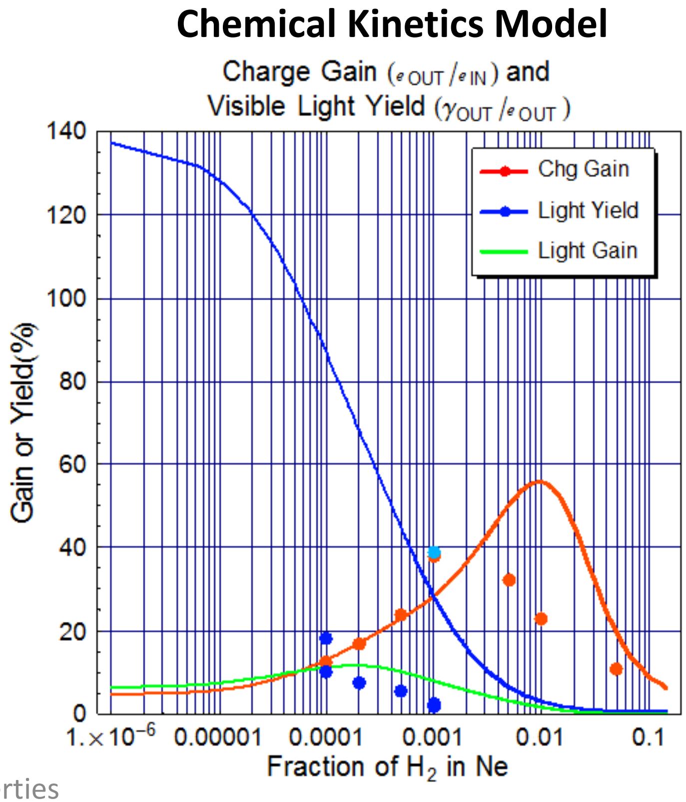
- Charge Gain and Light Yield both depend on H_2 concentration, but are relatively independent of temperature
- High Light Yield is maximized by varying both pressure and H_2 concentration
- 10 photons/electron at maximum
- A gas kinetic model can qualitatively predict the charge/light production

$$LightGain = Gain \times LightYield = \frac{N_{ph}}{N_0}$$

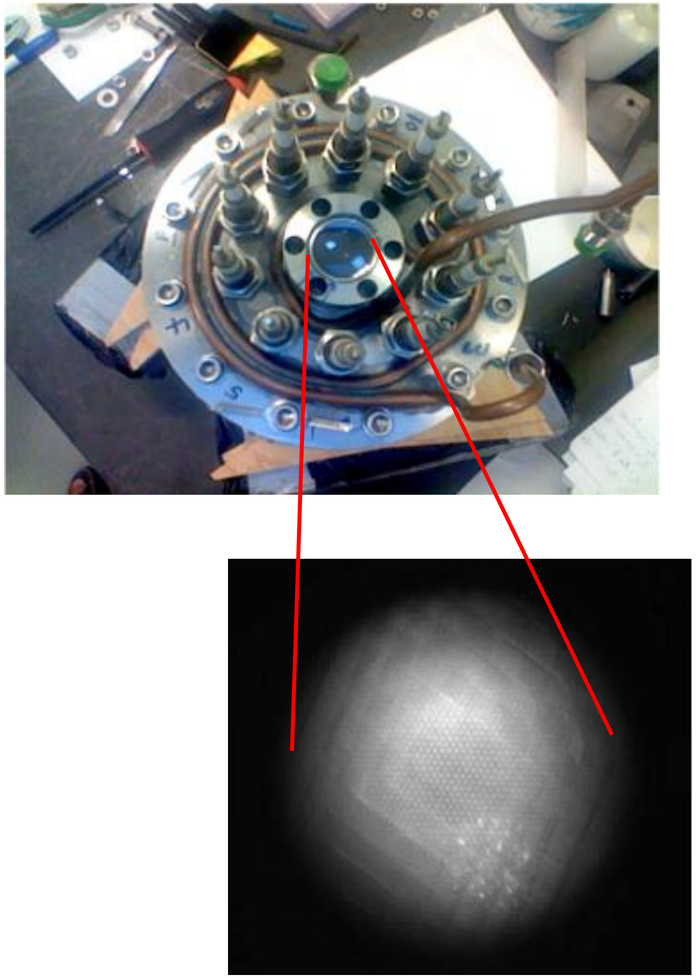
$$Ne^* + H_2 \rightarrow NeH_2^*$$
$$NeH_2^* \rightarrow Ne^* + H_2^+ + e^- \qquad High\ [H_2]$$

$$Ne^+ + H_2 \rightarrow NeH_2^+$$
$$NeH_2^+ \rightarrow NeH^* + H^+ + e^- \qquad Low\ [H_2]$$

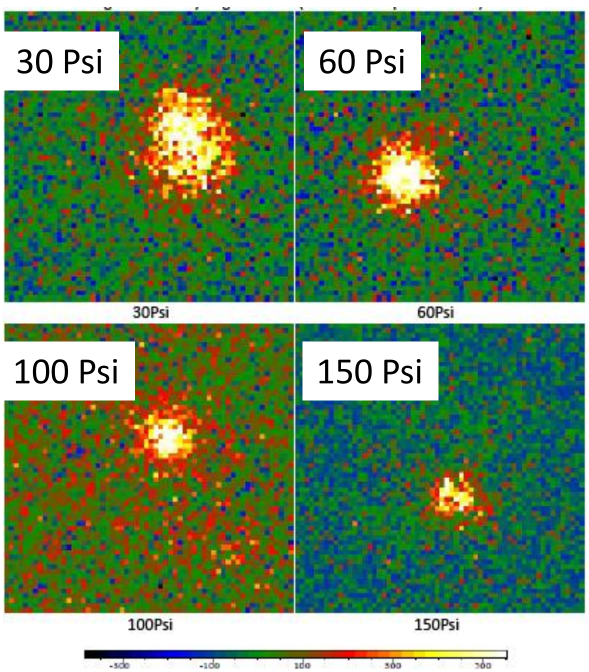




Optical Readout by EMCCD



- The EMCCD image shows good spatial resolution of GEM holes
- The cost of the optical readout can be significantly lower than electronic readout for large areas.



Resources

Noble Gas Detectors, Elena Aprile, Aleksey E. Bolotnikov, Alexander I. Bolozdynya, Tadayoshi Doke, John Wiley & Sons (2007)

Liquid State Electronics of Insulating Liquids**,** Werner F. Schmidt, CRC Press (1997)

See LBNE docdb 4482 for a recent summary of LAr properties

LBNE Working Group on
  LBNE FD/ND-SIM, Reconstruction, and charge/photon transport
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