Two-phase Cryogenic Avalanche Detector with electroluminescence gap and THGEM/GAPD-matrix multiplier

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Outline

1. Concept of two-phase Cryogenic Avalanche Detector (CRAD)

2. Recent results obtained using two-phase CRADs:
- Ionization yields in liquid Ar
- Proportional electroluminescence in two-phase Ar doped with N_2

3. Summary

Novosibirsk group presentation

Novosibirsk group on rare-event instrumentation operates within both Budker Institute of Nuclear Physics (BINP) and Novosibirsk State University (NSU), in the frame of Lab 3 (BINP) and LCEP (Laboratory of Cosmology and Elementary Particles of Physics Department of NSU).

Also, we have recently joined DarkSide20k collaboration.

Group management:
A. Buzulutskov (leader), A. Bondar (deputy director of BINP and dean of Physics Department of NSU), A. Dolgov (head of LCEP).

Group members:
A. Sokolov (senior scientist), L. Shekhtman (leading scientist), V. Nosov (engineer), R. Snopkov (engineer), E. Shemyakina (PHD student), V. Oleinikov (PHD student), A.Chegodaev (technician).

We also collaborate with S. Polosatkin and E. Grishnyaev from Plasma Division (BINP) on DD neutron generator development.

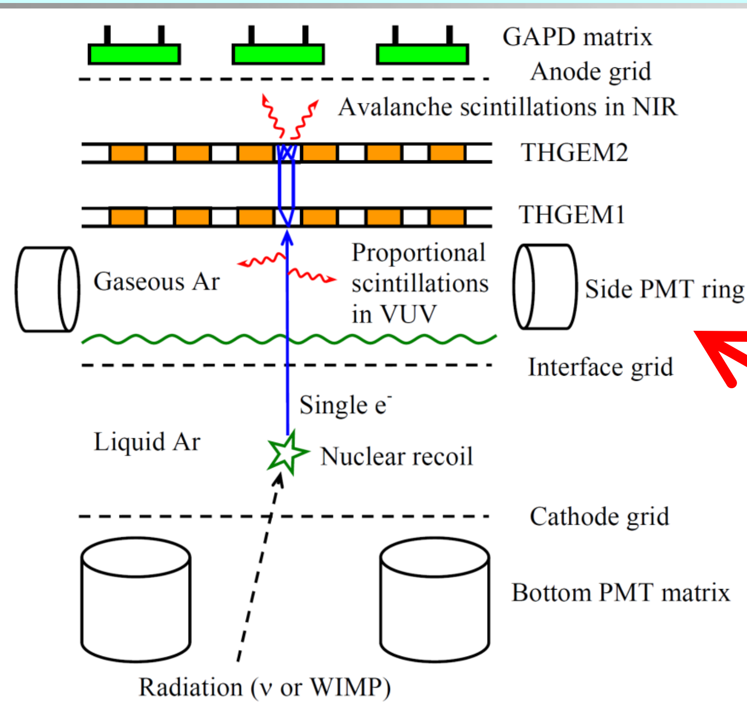
Our global objective

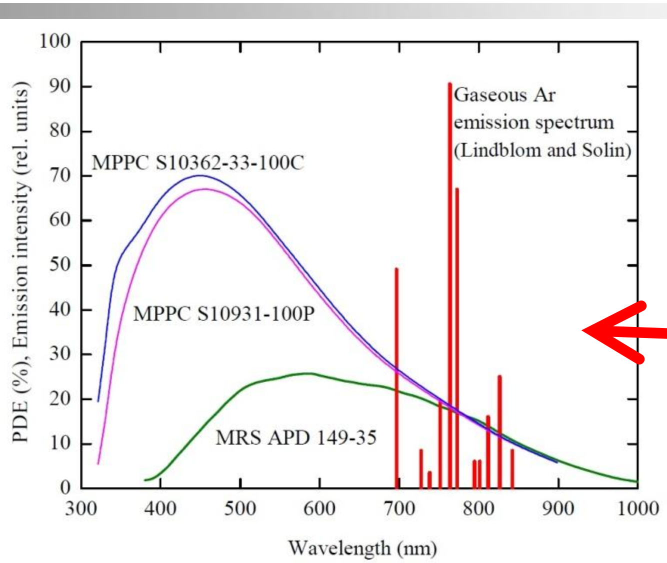
Development and energy calibration of liquid Ar detectors of ultimate sensitivity for dark matter search and coherent neutrino nucleus scattering experiments.

That means the development of nuclear recoil detectors capable to operate in single-electron and single-photon counting mode and their energy calibration at lower energies.

Two-phase Cryogenic Avalanche Detector (CRAD) of ultimate sensitivity: the concepts

Our detector concept: two-phase CRAD in Ar with EL gap and THGEM/GAPD-matrix multiplier for rare-event experiments



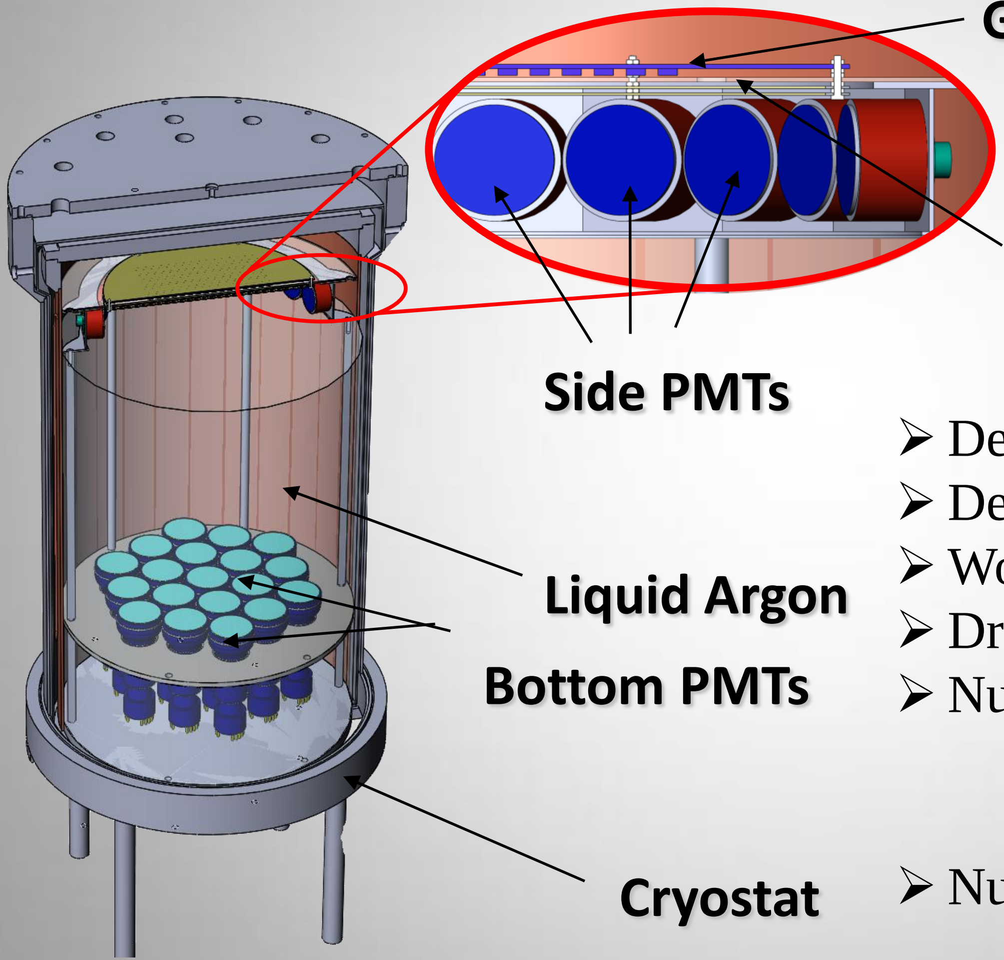


Concept: Detector of nuclear recoils of ultimate sensitivity for Coherent Neutrino-Nucleus Scattering and Dark Matter Search experiments
→ Two-phase Cryogenic Avalanche Detector (CRAD) in Ar with electroluminescence (EL) gap and THGEM/GAPD-matrix multiplier

Principle:
- Combining THGEM/GAPD-matrix readout with PMT readout of proportional EL, of the ionization (S2) signal, in single-electron counting mode
[Budker INP: A. Bondar et al, JINST 5 (2010) P08002; A.Buzulutskov et al, EPL 94 (2011) 52001]

- Final goal is to develop nuclear-recoil detectors of ultimate sensitivity, i.e. operating in single-electron counting mode with superior spatial resolution
- Single-electron counting capability is provided by EL scintillations recorded with PMTs, while superior spatial resolution by combined (charge/optical) THGEM/GAPD-matrix multiplier
- In Ar, we can use GAPDs without WLS due to intense avalanche scintillations in the NIR

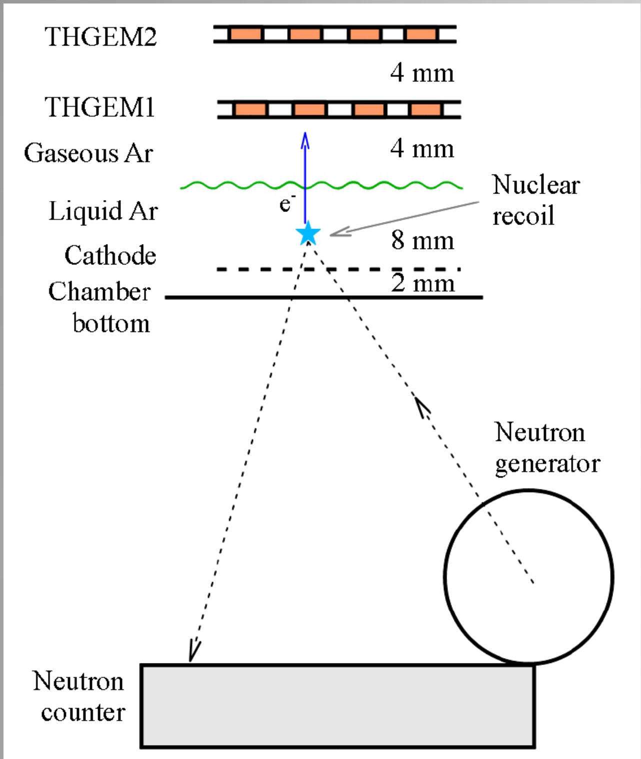
Two-phase CRAD in Ar: elaborated project with 160 l cryogenic chamber – 3D view



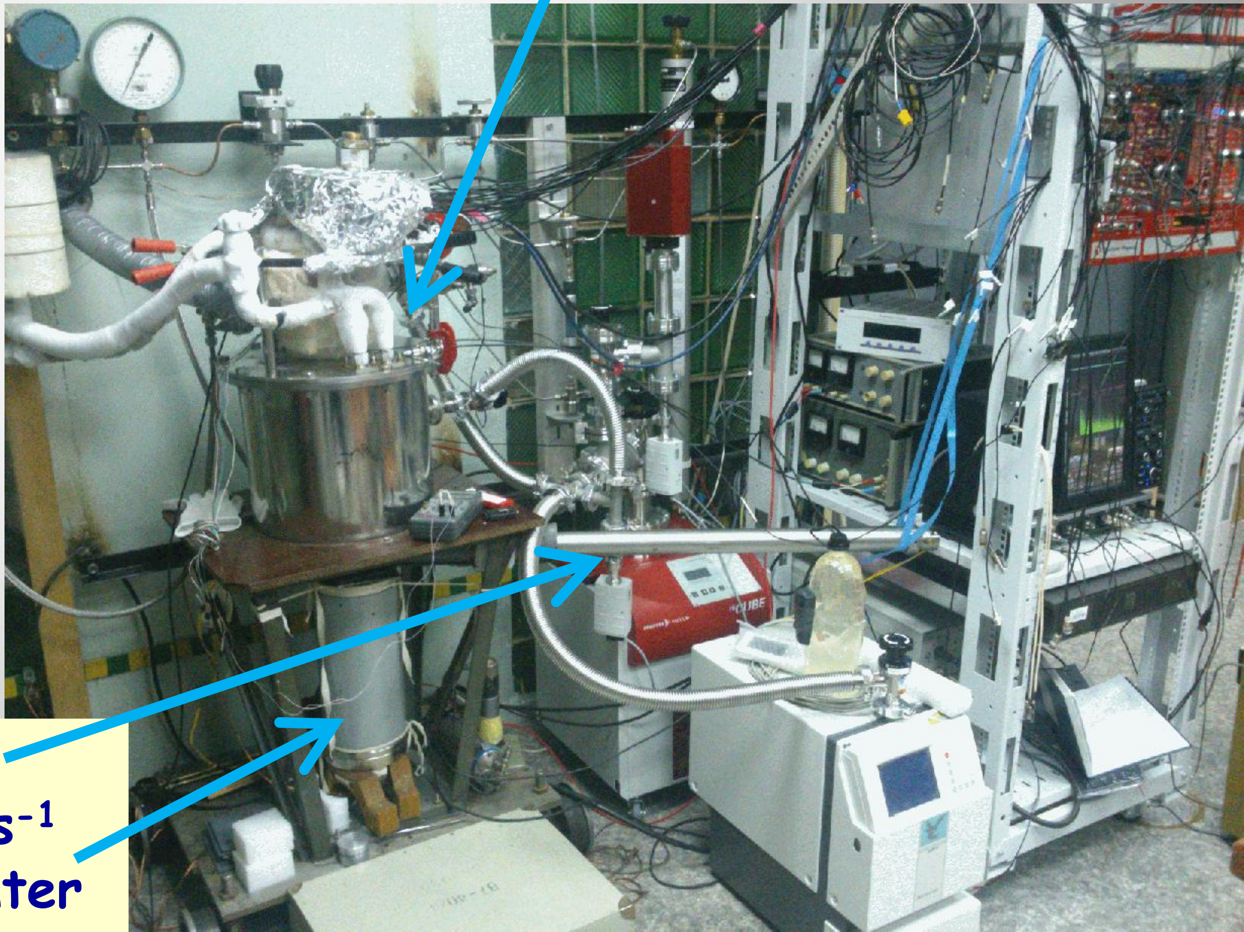
- Detector total volume - 160 l
- Detector fiducial volume – 50 l
- Working temperature – 87 K
- Drift field – 2 kV/cm
- Number of photomultipliers:
  - side 20
  - bottom 19
- Number of GAPDs – 512

Ionization yield from liquid Ar due to nuclear and electron recoil

First measurement of ionization yield of nuclear recoils in liquid Ar at higher energies: experimental setup

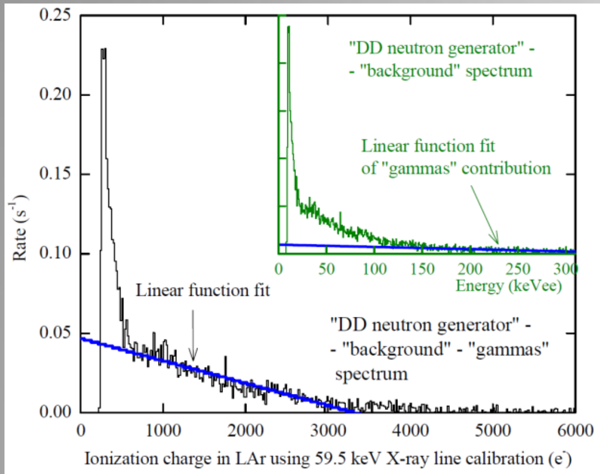


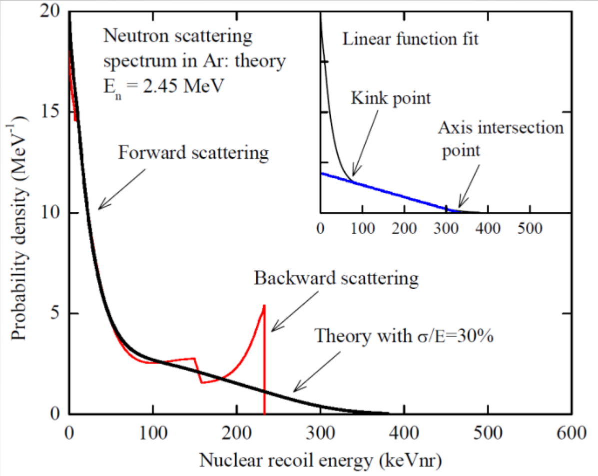
First use of <u>two-phase CRAD</u> in Ar with THGEM-based charge readout in dark matter-related (energy calibration) experiment



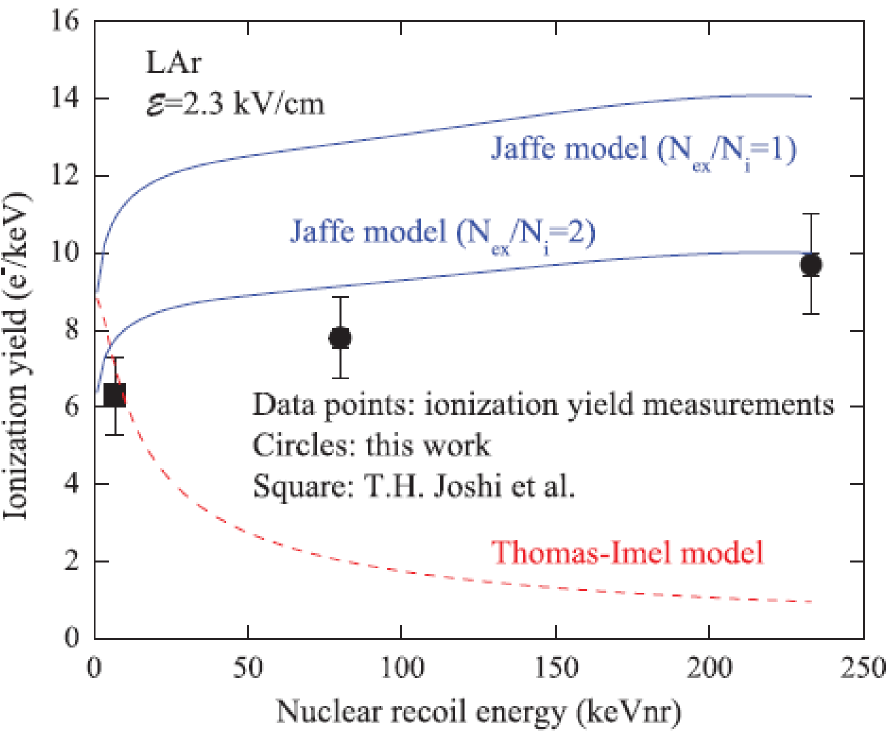
- DD neutron generator: 2.45 MeV neutrons, 10^4 s^{-1}
- Neutron (stilbene) counter

First measurement of ionization yield of nuclear recoils in liquid Ar at higher energies: results [EPL 108 (2014) 12001]





Experimental spectrum compared to that of theoretical at two characteristic spectrum points – 80 and 233 keV



Ionization quench factor:
0.27 and 0.30 at 80 and 233 keV

Ionization yield:
7.8 and 9.7 e-/keV at 80 and 233 keV

Energy dependence is well described by Jaffe model (in contrast to that of Thomas-Imel)

First systematic study of ionization yields of electron recoils in liquid Ar [Eprint arXiv:1505.02296]

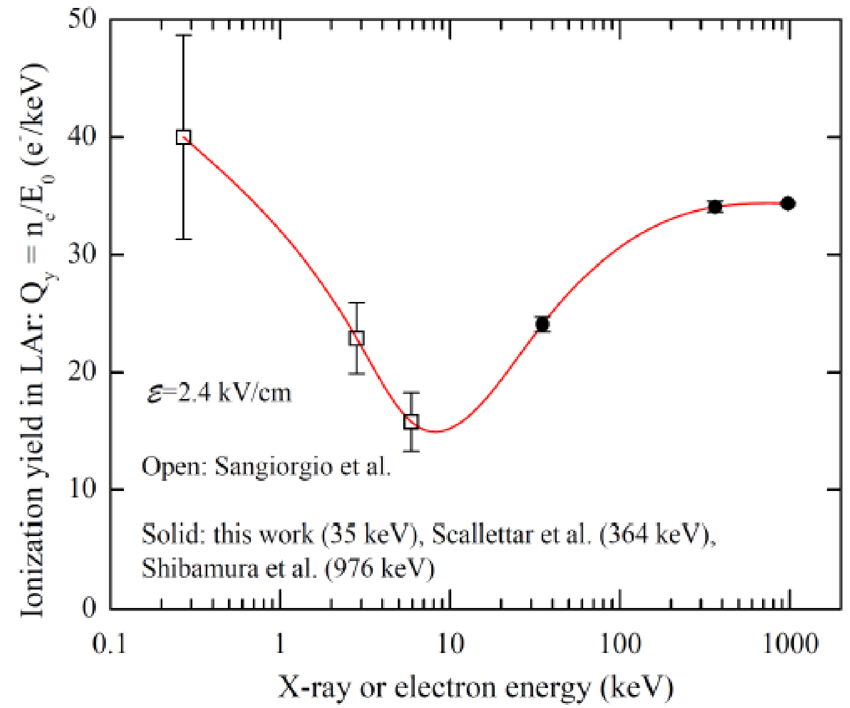


Fig.7 Summary of absolute ionization yields in liquid Ar for electron recoils, due to X-ray or electron irradiation, as a function of the X-ray or electron energy, at an electric field of 2.4 kV/cm. The data points were directly measured at lower energies in Sangiorgio et al. [11] (at 0.27 keV, 2.8 keV and 5.9 keV) and calculated using recombination coefficients at higher energies in this work (at 35 keV), Scallettar et al. [21] (at 364 keV) and Shibamura et al. [17] (at 976 keV). The solid line is the spline function fit to the combined data points.

Remarkable energy dependence of the ionization yield: the yield has a minimum at 10 keV → It should be described by combining the Jaffe and Thomas-Imel recombination models (presenting the opposite energy dependence).

Recent results: measurement of ionization yields in liquid Ar

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

October 2014

EPL, **108** (2014) 12001 www.epljournal.org
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Measurement of the ionization yield of nuclear recoils in liquid argon at 80 and 233 keV

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PACS 29.40.-n – Radiation detectors
PACS 95.55.Vj – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors
PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological)

Abstract – The energy calibration of nuclear recoil detectors is of primary importance to rare-event experiments such as those of direct dark matter search and coherent neutrino-nucleus scattering. In particular, such a calibration is performed by measuring the ionization yield of nuclear recoils in liquid Ar and Xe detection media, using neutron elastic scattering off nuclei. In the present work, the ionization yield for nuclear recoils in liquid Ar has for the first time been measured in the higher energy range, at 80 and 233 keV, using a two-phase Cryogenic Avalanche Detector (CRAD) and DD neutron generator. The ionization yield in liquid Ar at an electric field of 2.3 kV/cm amounted to 7.8±1.1 and 9.7±1.3 e^-/keV at 80 and 233 keV, respectively. The Jaffe model for nuclear recoil-induced ionization, in contrast to that of Thomas-Imel, can probably consistently describe the energy dependence of the ionization yield.

E-print arXiv:1505.02296

X-ray ionization yields and energy spectra in liquid argon

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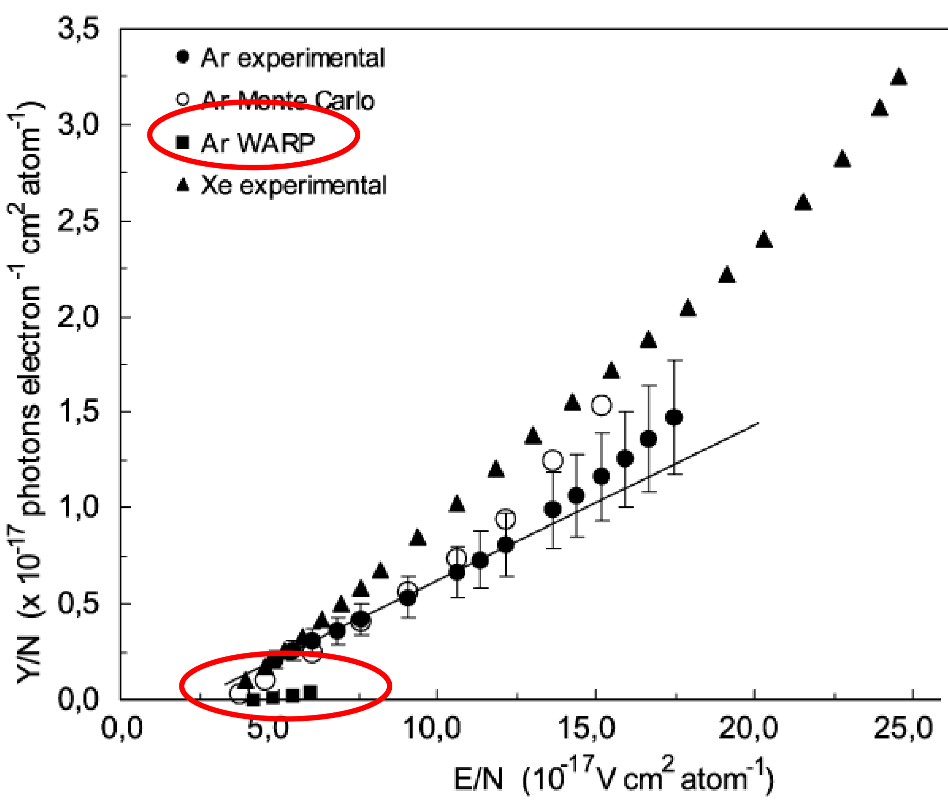
ABSTRACT: The main purpose of this work is to provide reference data on X-ray ionization yields and energy spectra in liquid Ar to the studies in the field of Cryogenic Avalanche Detectors (CRADs) for rare-event and other experiments, based on liquid Ar detectors. We present the results of two related researches. First, the X-ray recombination coefficients in the energy range of 10-1000 keV and ionization yields at different electric fields, between 0.6 and 2.3 kV/cm, are determined in liquid Ar based on the results of a dedicated experiment. Second, the energy spectra of pulsed X-rays in liquid Ar in the energy range of 15-40 keV, obtained in given experiments including that with the two-phase CRAD, are interpreted and compared to those calculated using a computer program, to correctly determine the absorbed X-ray energy. The X-ray recombination coefficients and ionization yields have for the first time been presented for liquid Ar in systematic way.

Measurements of ionization yields, both of nuclear recoils and electron recoils, are of paramount importance for energy calibration of dark matter search and coherent neutrino scattering detectors

Proportional electroluminescence in gaseous Ar

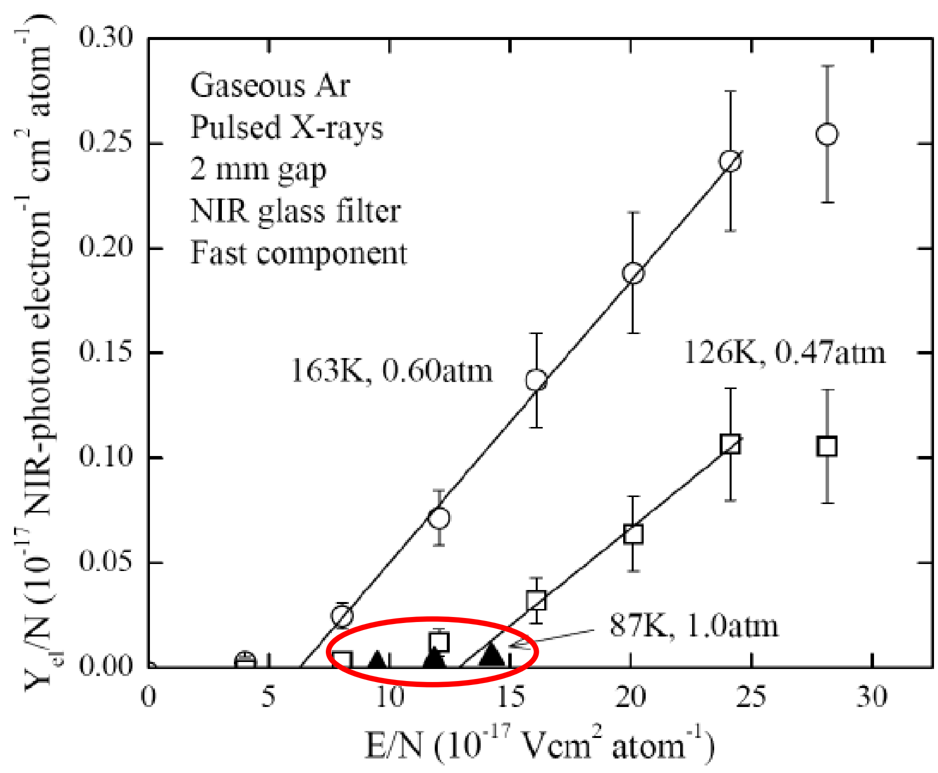
Motivation to study proportional EL: confusing data at LAr temperature

In the Vacuum Ultraviolet (VUV)



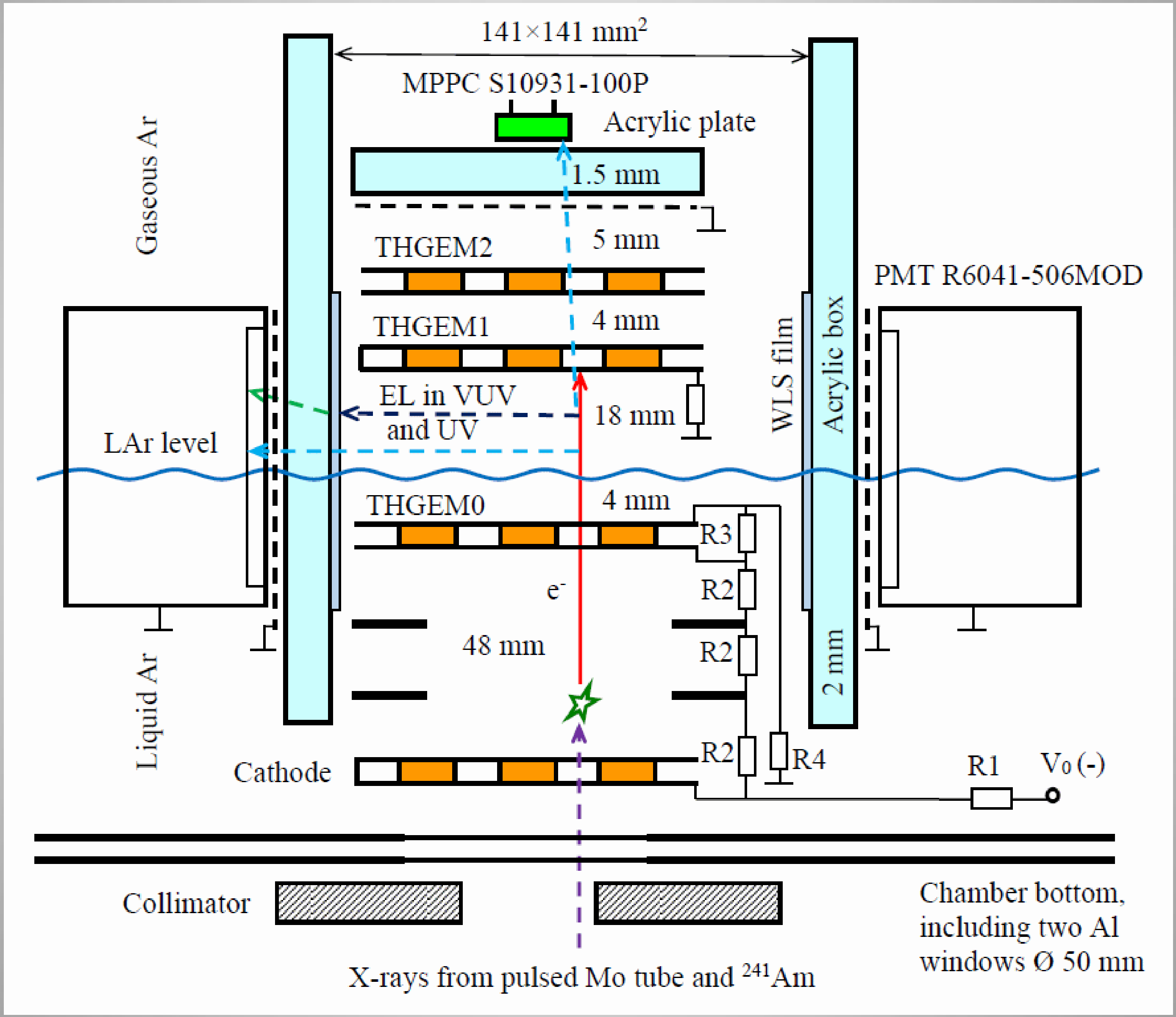
Physics Letters B 668 (2008) 167–170

In the Near Infrared (NIR) [2012 JINST 7 P06014]

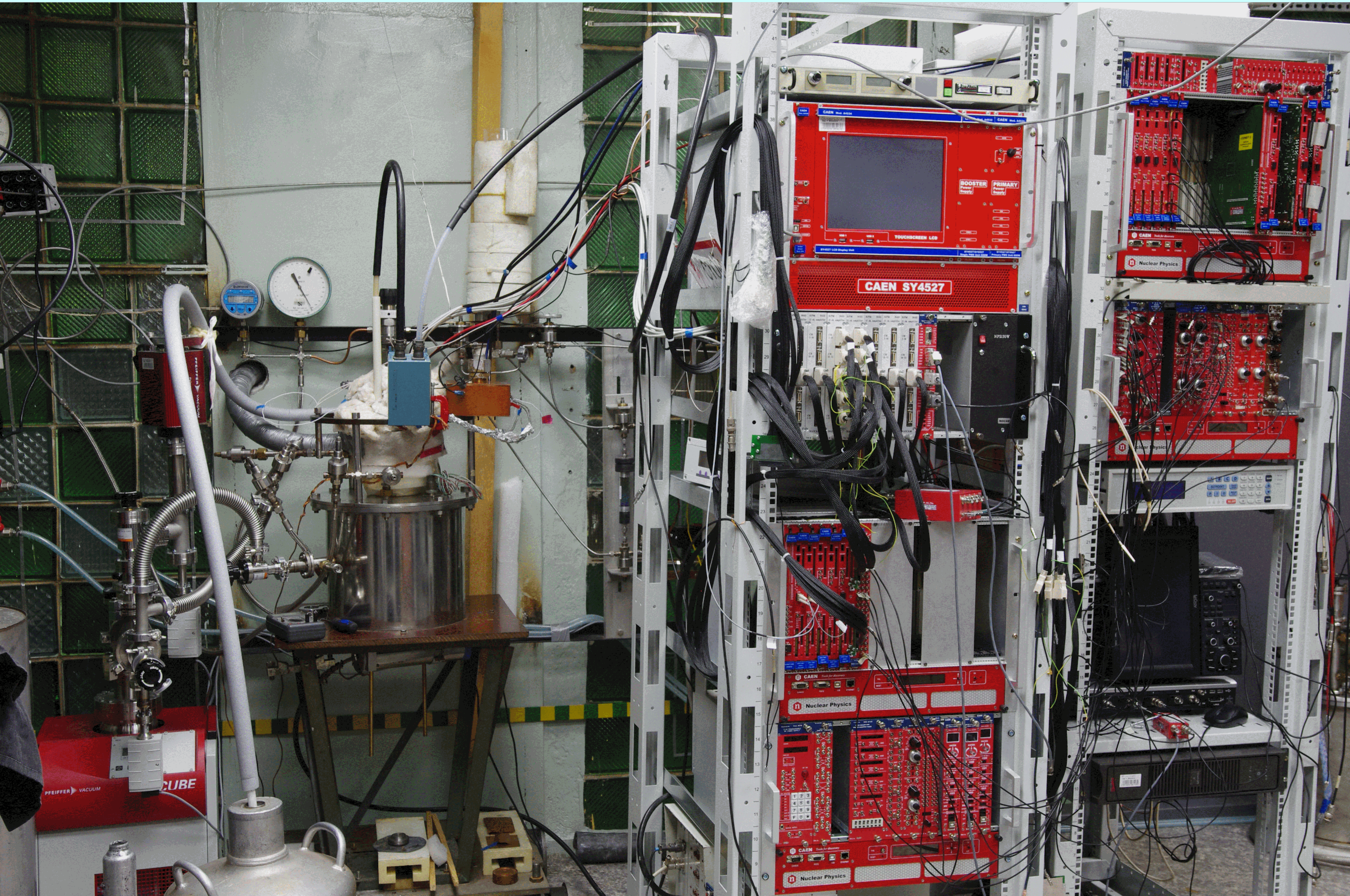


Confusing data: the EL yield is suppressed at 87K compared to higher temperatures, both in the VUV and NIR

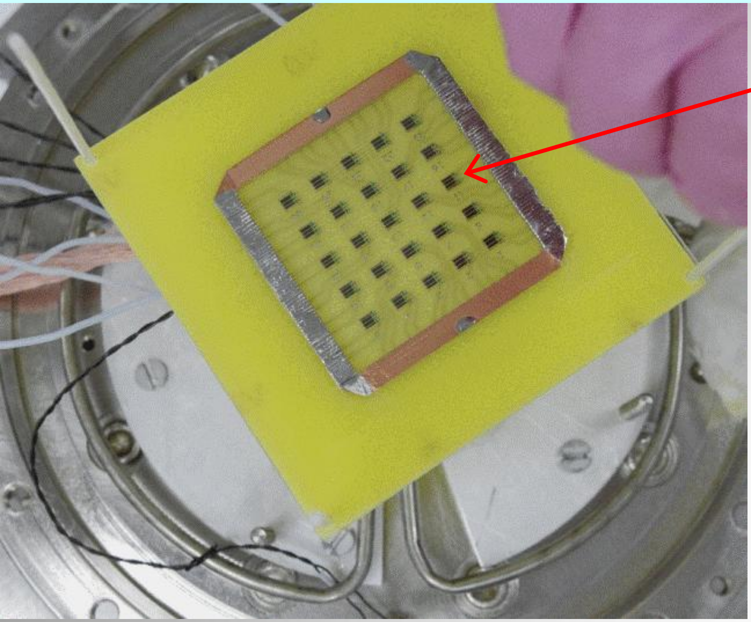
Experimental setup



Experimental setup of two-phase CRAD with 9 l cryogenic chamber for 2014-2016 measurement campaigns



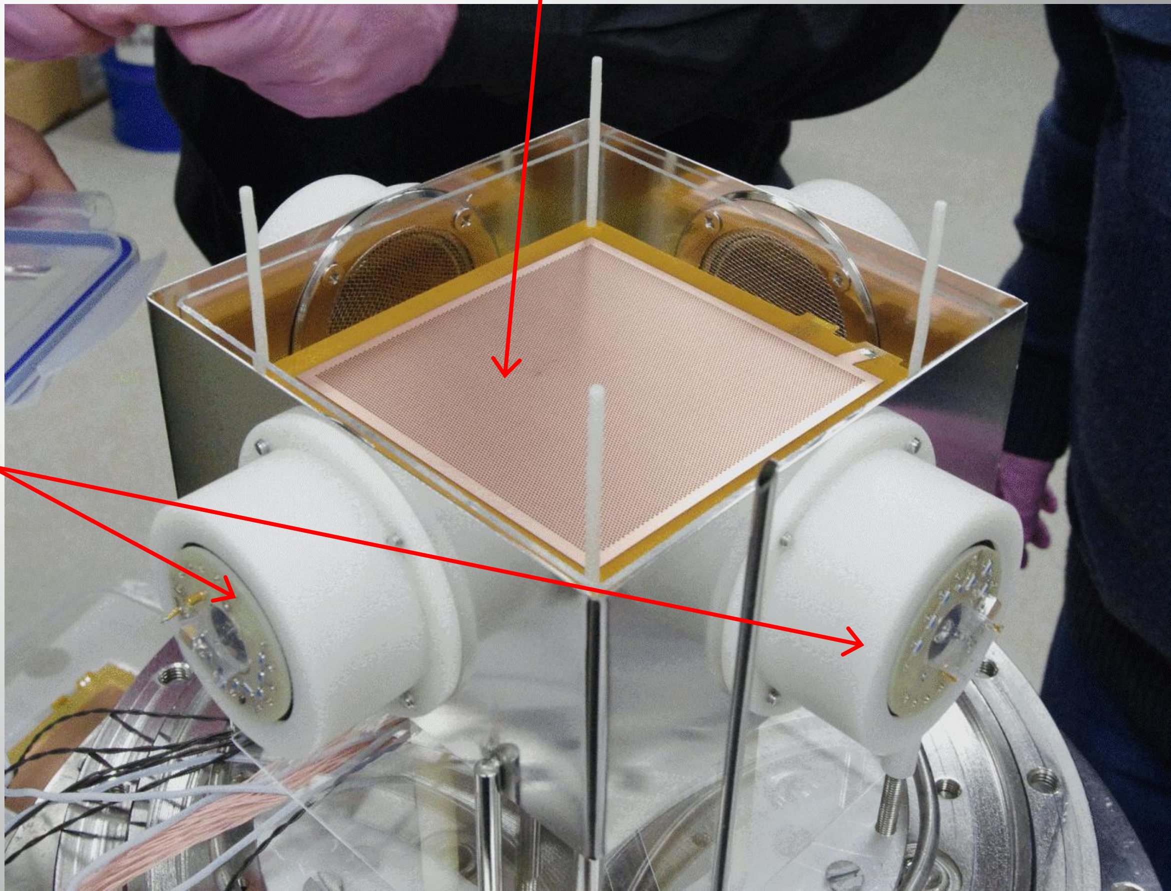
Experimental setup



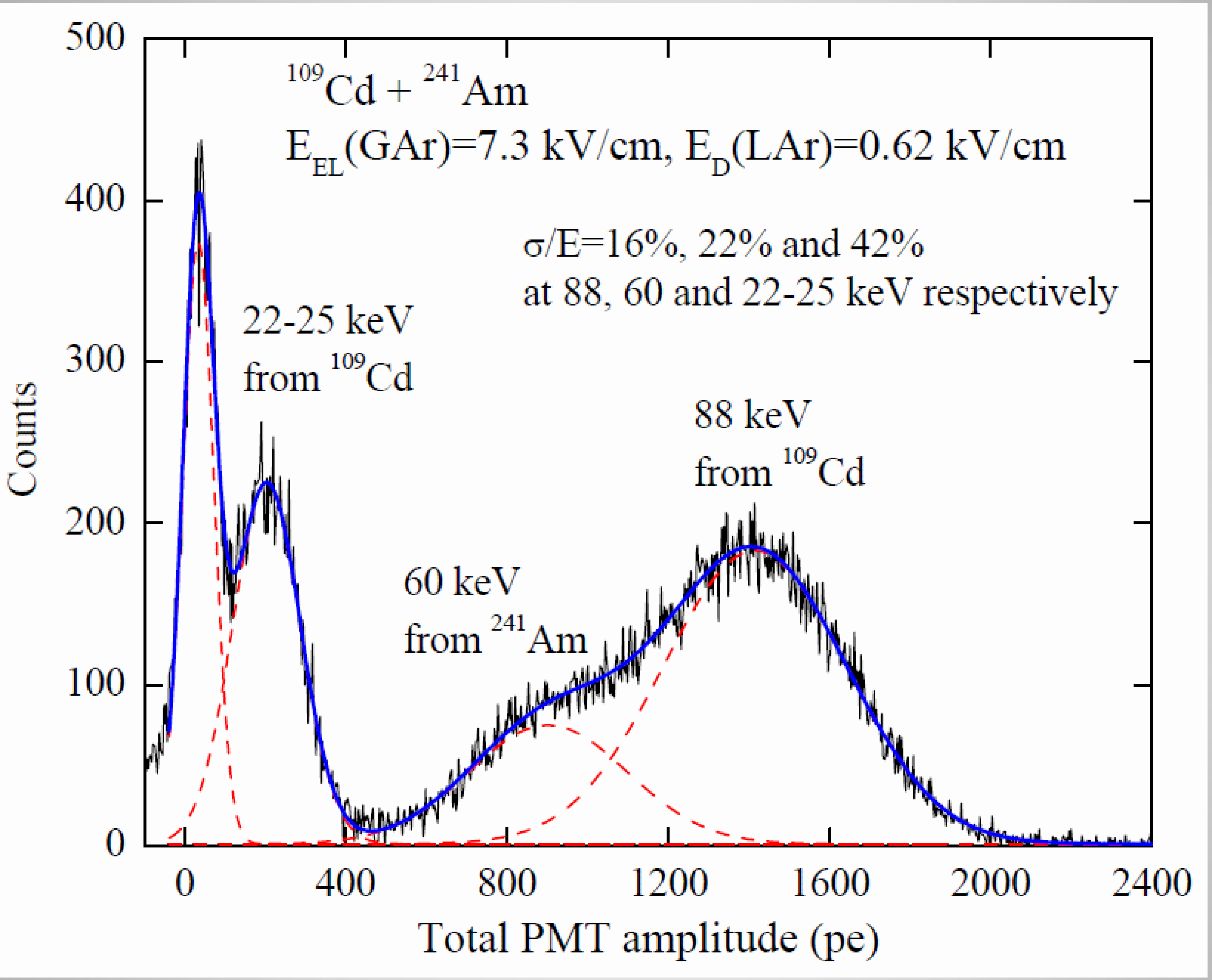
GAPD 5x5 matrix: Hamamatsu S10931-100P

Extraction grid: THGEM

PMT: Hamamatsu R6041-506-MOD

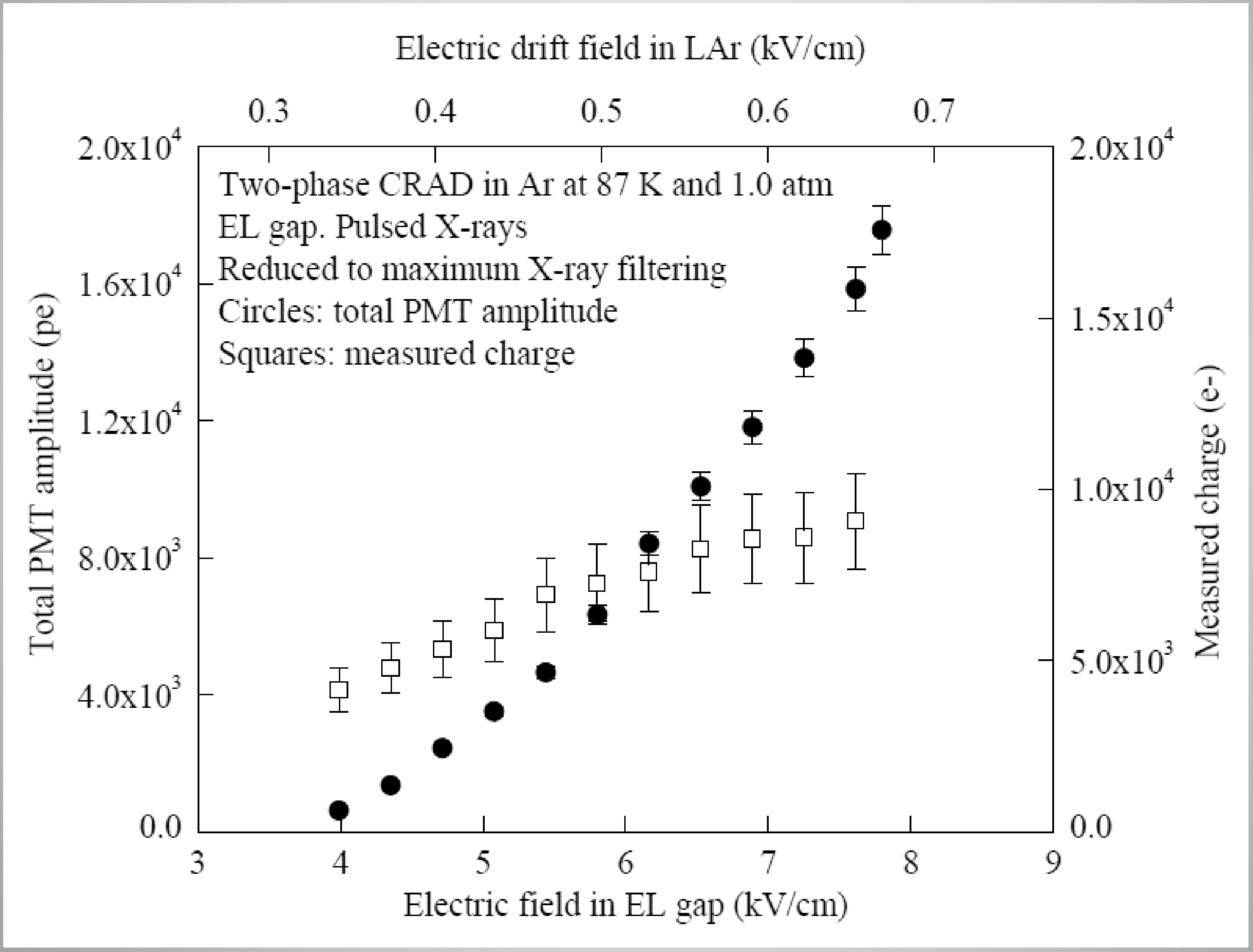


^{109}Cd and ^{241}Am gamma-ray spectrum using S2 (proportional EL) signal

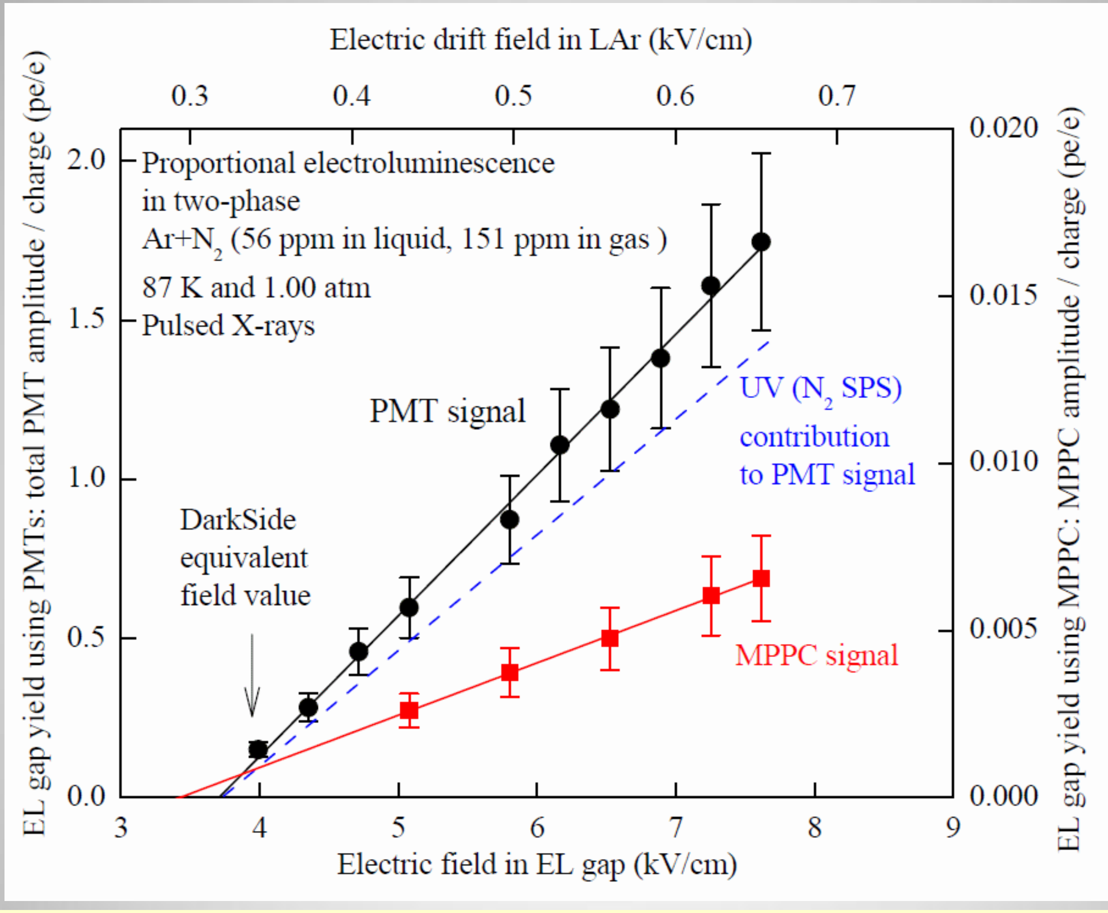


- High EL gap yield: 15 pe/keV
- Good energy resolution: 22% at 60 keV

Proportional EL in two-phase Ar: Light and charge signal dependence on field



EL gap yield: PMT vs MPPC signal



- High EL gap yield, reaching 1.5 pe/e at 7 kV/cm
- The PMT signal amplitude is a factor of 3 larger than expected from VUV emission due to Ar excimers
- The presence of the MPPC signal indicates on the substantial non-VUV contribution, presumably due to N2 emission in the near UV

Ar and N_2 energy levels

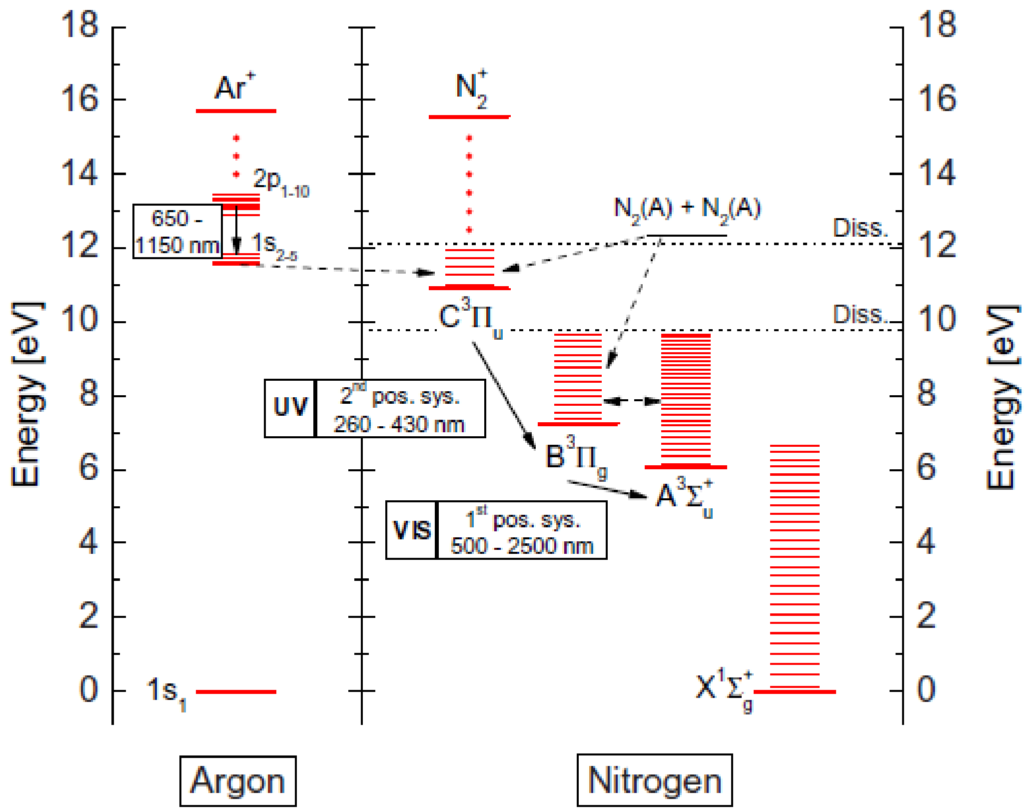


Figure 3. Relevant energy levels for argon [25] and molecular nitrogen [26] including vibrational states for N_2, ionization and dissociation energies, prominent optical transitions (solid arrows) and heavy-particle reactions (dashed arrows). The level named '$N_2(A) + N_2(A)$' illustrates the minimal energy level for two colliding metastable nitrogen molecules.

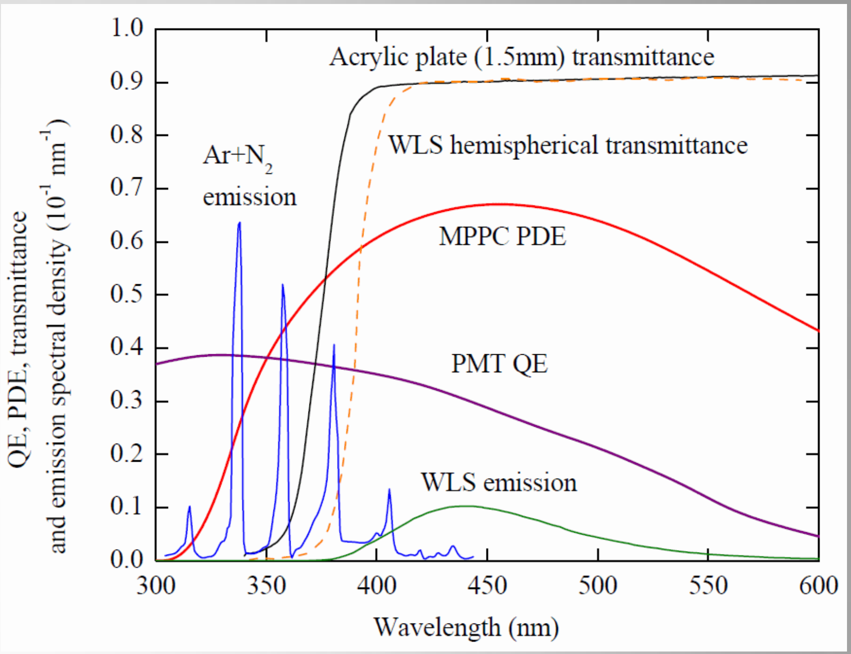
New Journal of Physics **14** (2012) 043016

Proportional EL in two-phase Ar in presence of N_2

T. Takahashi et al., NIM 205 (1983) 591:

In presence of N_2 admixture in gaseous Ar at high (~1 atm) pressures the mechanism of proportional electroluminescence may change its nature, namely the excimer production (and hence the VUV emission) can be taken over by that of excited N_2 molecules in two-body collisions [17], followed by their de-excitations through the emission of the so-called Second Positive System (SPS) [18], at 300-450 nm [17]:

$$Ar^*(3p^5 4s^1) + N_2 \to Ar + N_2^*(C^3\Pi_u), \qquad (2)$$
$$N_2^*(C^3\Pi_u) \to N_2^*(B^3\Pi_g) + h\nu \ .$$



N_2 Second Positive System (SPS) emission in the UV (300-450 nm):

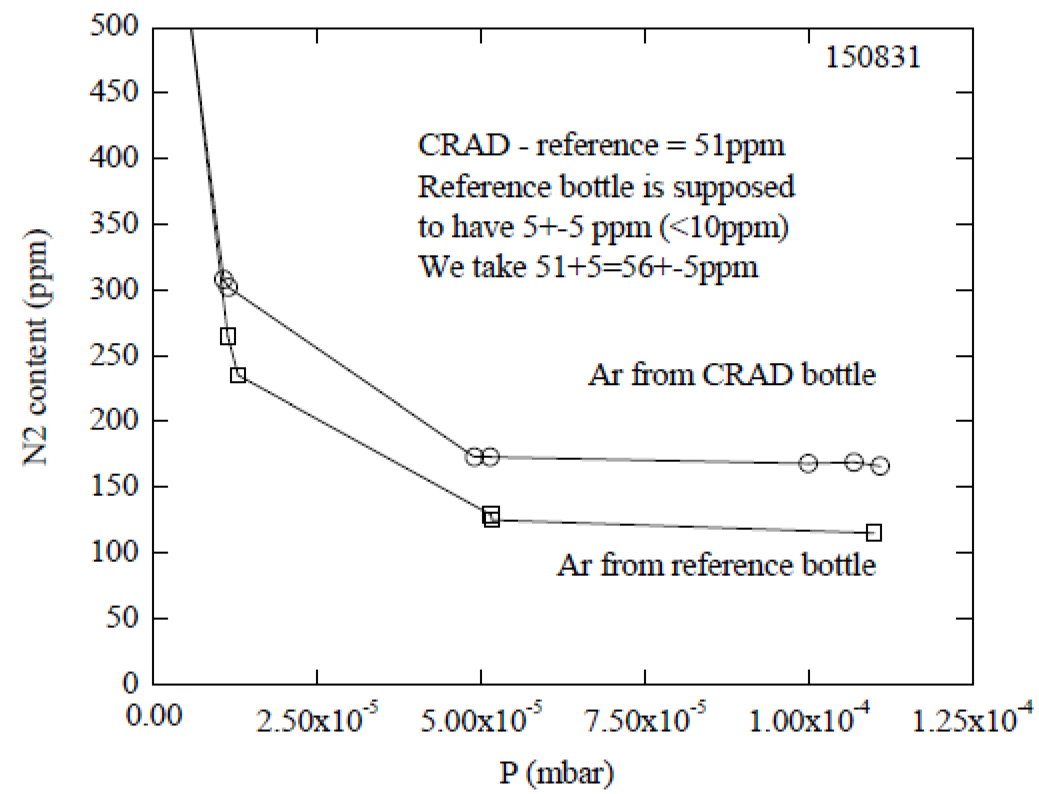
$$Ar^*(3p^5 4s^1) + N_2 \to Ar + N_2^*(C^3\Pi_u)$$
$$N_2^*(C^3\Pi_u) \to N_2^*(B^3\Pi_g) + h\nu$$

Hypothesis of combined Ar excimer and N_2 SPS emission

Accordingly, we adopt here the hypothesis that there were two principal sources of the EL emission in two-phase Ar in our experiment: first, due to Ar excimer emission in the VUV (at 128 nm) and, second, due to N_2 Second Positive System (SPS) emission in the UV (at 300-450 nm)

This hypothesis requires three spectral components contributing to the EL gap yield using the PMTs, namely those of the VUV and UV, absorbed and reemitted in the WLS, and that of the UV escaping absorption in the WLS.

N_2 content measurement at ppm level



Residual Gas Analyzer technique

Отчет хроматограммы

Паспорт хроматограммы

Проект:	ДТП 12	**Колонка:**	Цеолиты СаА
Название метода:		**Проба:**	Аргон 40 литров 266
Дата и время:	19.10.2015 15:06:02	**Метод расчета:**	Абсолютная градуировка
Анализ.Хроматограмма:	67.1	**Объем, мкл:**	1000
Оператор:		**Разведение:**	1
		Источник:	
Комментарии:	Предположительно 56ppm Азота		

Режим прибора

```
[ МЕТОДИКА ]
Продолжительность анализа #1: 00:30:00
Продолжительность анализа #2: 00:20:00
Колонка,       °C: 30,00
Детектор 1,    °C: 130,00
Испаритель 2,  °C: 50,00
Детектор 2,    °C: 130,00
Расход газа-1 (Азот),  мл/мин: 20,00
Расход газа-2 (Гелий),  мл/мин: 20,00
Расход газа-3 (Гелий),  мл/мин: 20,00
Расход газа-4 (Гелий),  мл/мин: 20,00
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[ ПЕРИФЕРИЯ: Краны ]
Кран-переключатель, °C : 100,0
Метанатор, °C          : 100,0
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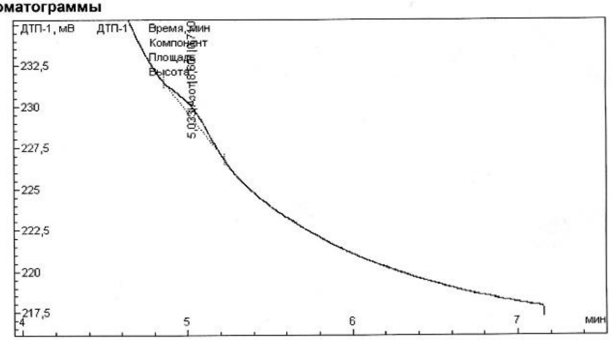
Компоненты

Время, мин	Название	Окно, %	Концентрация	Ед. концентрации	K1	Отклик	Группа	Детектор
5.033	Азот	5	25	ppm		Площадь		ДТП-1

Хроматограммы

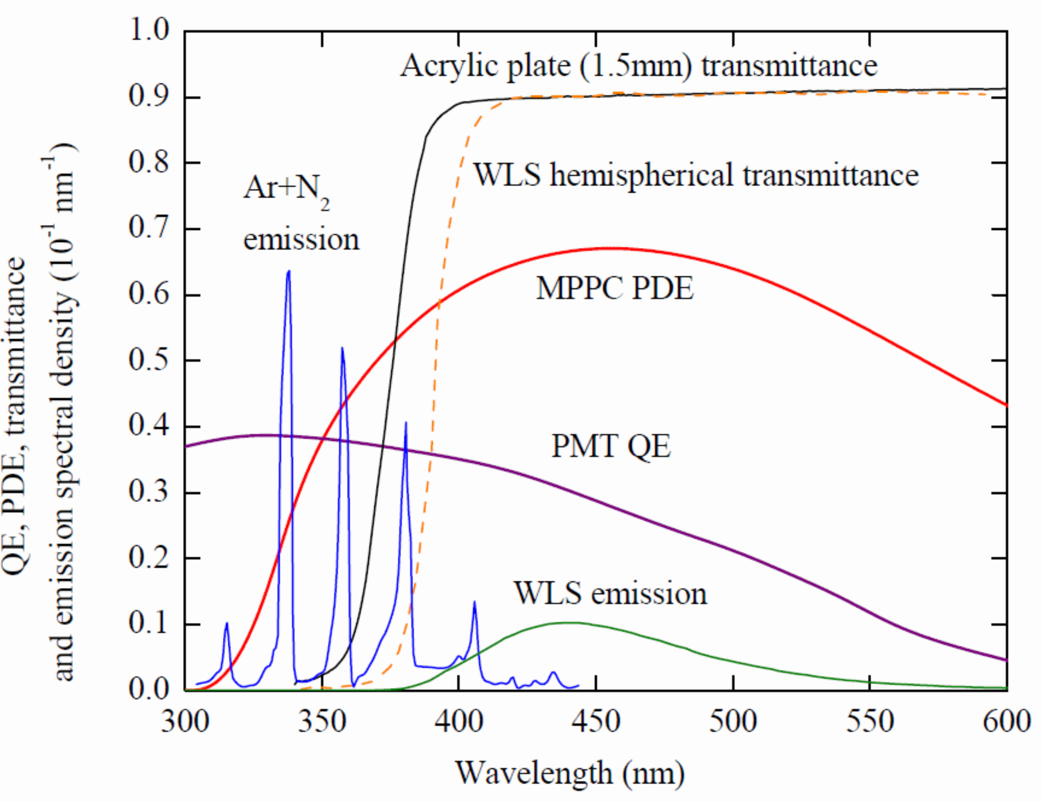


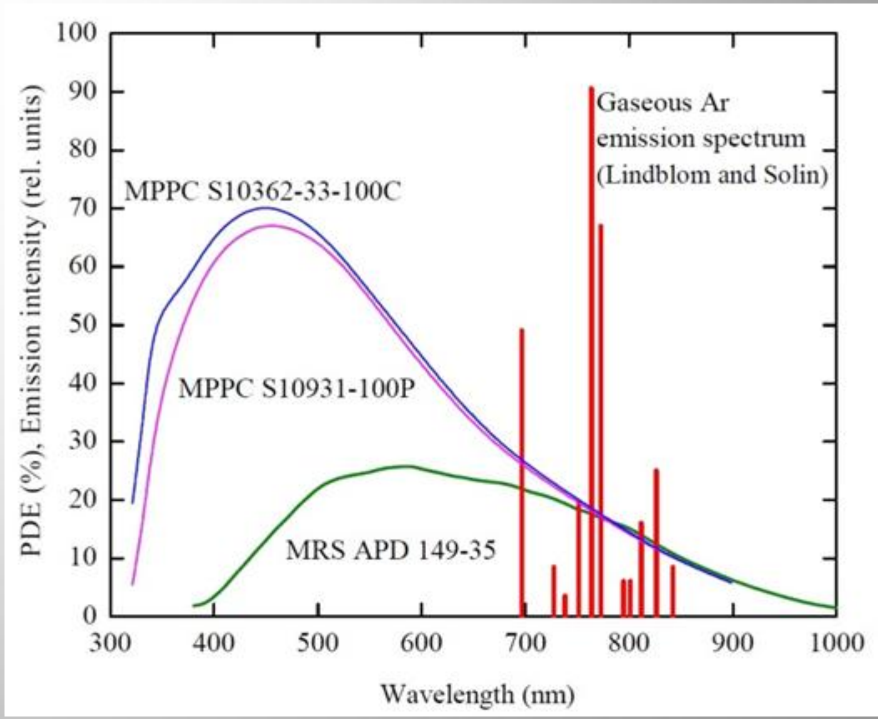
22.10.2015 17:00:54

Chromatography technique

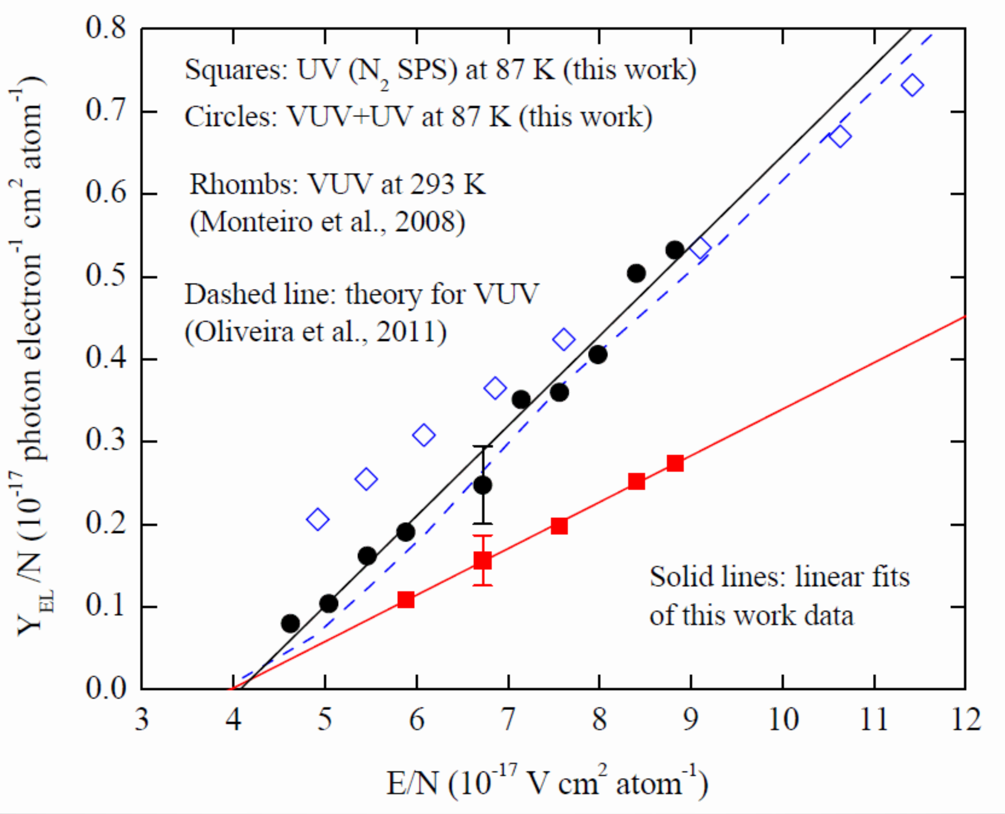
Average N2 content value from both techniques:
(56+42)/2 = 49+-7 ppm

Optical spectra





Absolute EL yield in two-phase Ar doped with N2



In two-phase Ar doped with N2 (49 ppm in LAr and 130 ppm in GAr according to Rault's law), proportional EL has an amplification parameter of 109+-10 photons per drifting electron per kV overall in the VUV and UV, of which 51% were emitted in the UV (N2 SPS). The overall amplification parameter and the EL threshold (3.7 kV/cm) are in good accordance with the theory of Oliveira et al.

Conclusions on proportional EL in two-phase Ar

The effect of N_2 doping on proportional EL in Ar is enhanced at lower temperatures.

The S2 (proportional EL) signal response was found to be substantially enhanced due to the fraction of the N_2 emission spectrum recorded directly, compared to that of reemitted in WLS.

In this regard, of particular interest is the idea to replace all cryogenic PMTs with GAPDs (SiPMs, MPPCs) that have high sensitivity in the N_2 emission region (in the near UV, see optical spectra slide).

Recent results: first systematic study of proportional EL in two-phase Ar

epl A Letters Journal Exploring the Frontiers of Physics

October 2015

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doi: 10.1209/0295-5075/112/19001

Proportional electroluminescence in two-phase argon and its relevance to rare-event experiments

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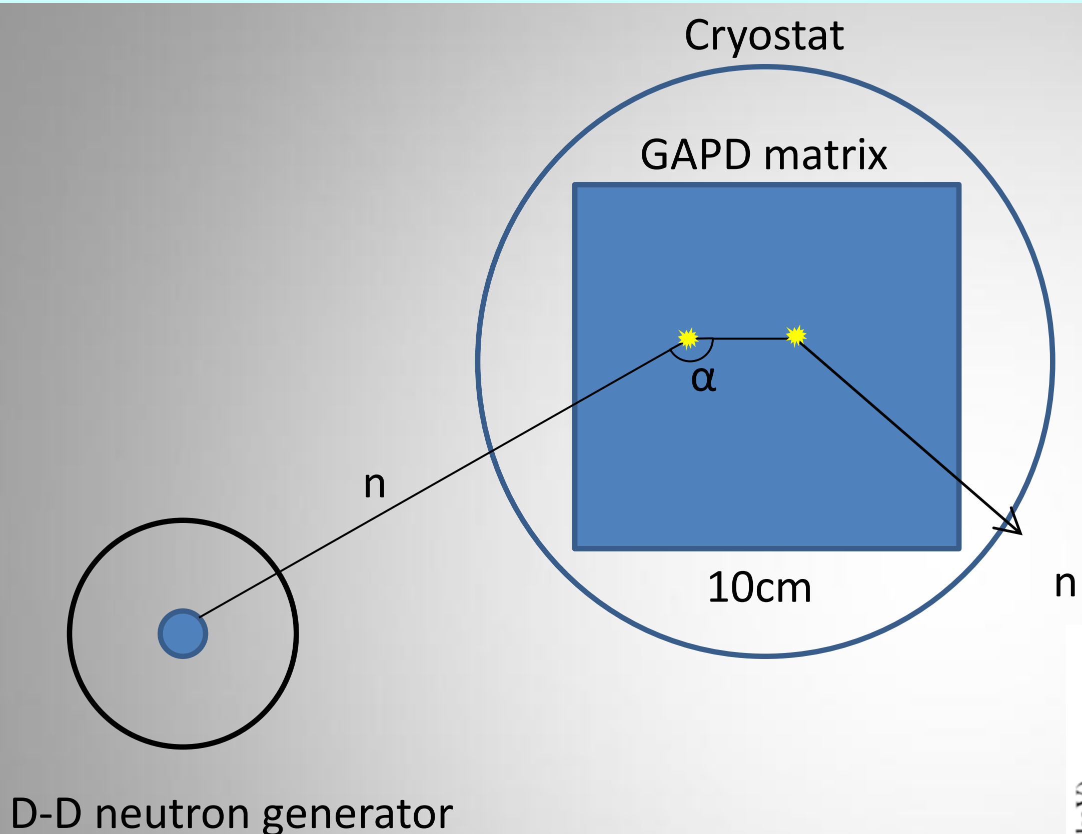
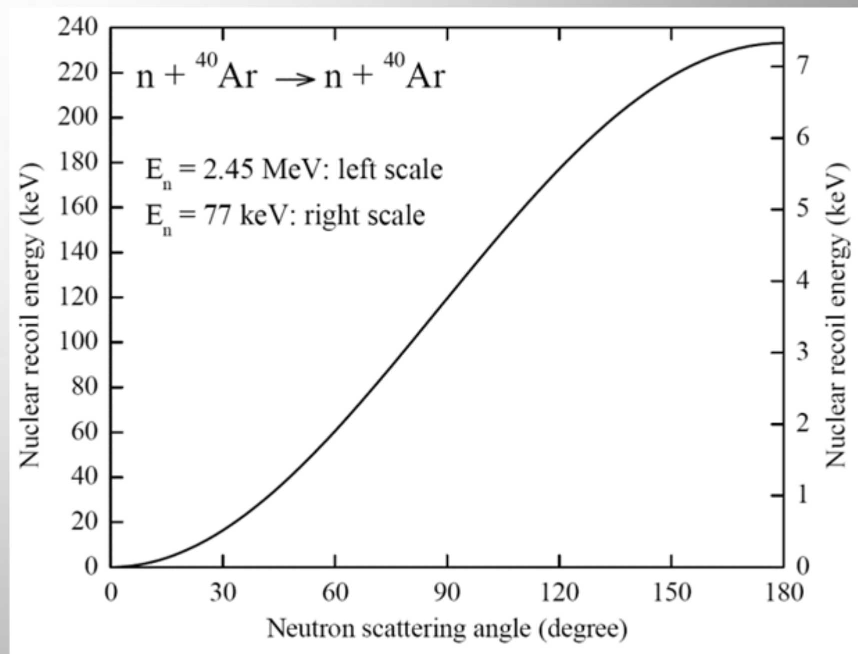
PACS 95.55.Vj – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors
PACS 61.25.Bi – Liquid noble gases
PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological)

Abstract – Proportional electroluminescence (EL) in gaseous Ar has for the first time been systematically studied in the two-phase mode, at 87 K and 1.00 atm. Liquid argon had a minor (56 ppm) admixture of nitrogen, which allowed to understand, *inter alia*, the effect of N_2 doping on the EL mechanism in rare-event experiments using two-phase Ar detectors. The measurements were performed in a two-phase cryogenic avalanche detector (CRAD) with EL gap located directly above the liquid-gas interface. The EL gap was optically read out in the vacuum ultraviolet (VUV), near 128 nm (Ar excimer emission), and in the near ultraviolet (UV), at 300–450 nm (N_2 second positive system emission), via cryogenic photomultiplier tubes (PMTs) and a Geiger-mode APD (GAPD). Proportional electroluminescence was measured to have an amplification parameter of 109 ± 10 photons per drifting electron per kV overall in the VUV and UV, of which $51 \pm 6\%$ were emitted in the UV. The measured EL threshold, at an electric field of 3.7 ± 0.2 kV/cm, was in accordance with that predicted by the theory. The latter result is particularly relevant to DarkSide and SCENE dark matter search-related experiments, where the operation electric field was thereby on the verge of appearance of the S2 (ionization-induced) signal. The results obtained pave the way to the development of N_2-doped two-phase Ar detectors with enhanced sensitivity to the S2 signal.

Neutron double-scattering concept for energy calibration at low energies



Having high spatial resolution in CRAD, of 1 mm, one can reach accuracy of about 2° in scattering angle, corresponding to nuclear recoil energy as low as a few keV



Summary

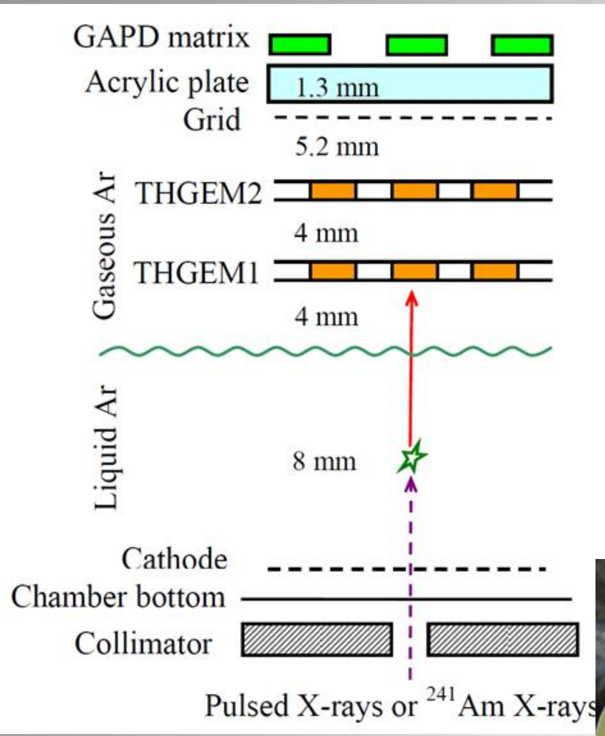
Advanced two-phase CRAD, with EL gap and THGEM/GAPD-matrix multiplier, showed very promising performance in Ar in terms of high sensitivity. Of particular interest is that doped with a minor (50 ppm) admixture of N_2, presenting enhanced EL yield due to emission in the near UV.

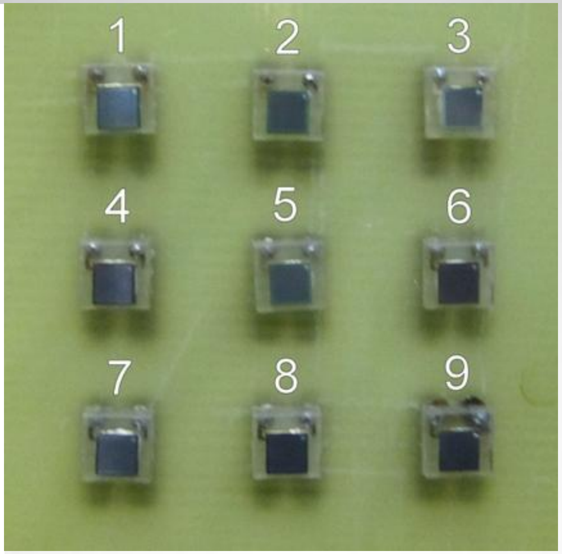
Ionization yields of nuclear recoils in liquid Ar have for the first time been measured at higher energies using neutron scattering. Those of electron recoils have been also studied in systematic way.

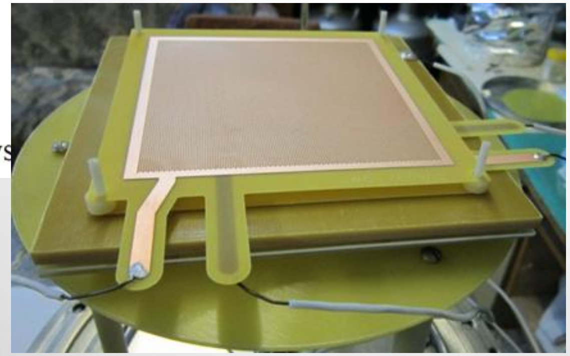
These results pave the way to the development of N_2-doped two-phase Ar detectors with enhanced sensitivity to ionization (S2) signal, for dark matter search and low-energy neutrino experiments.

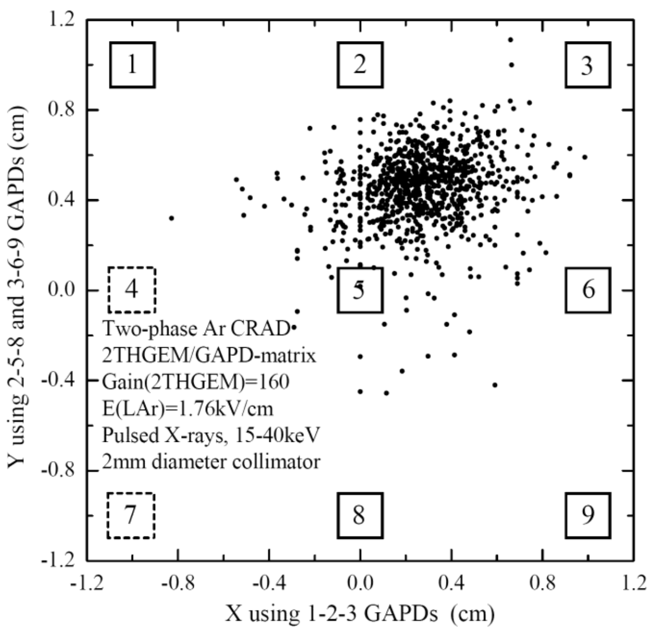
Backup slides

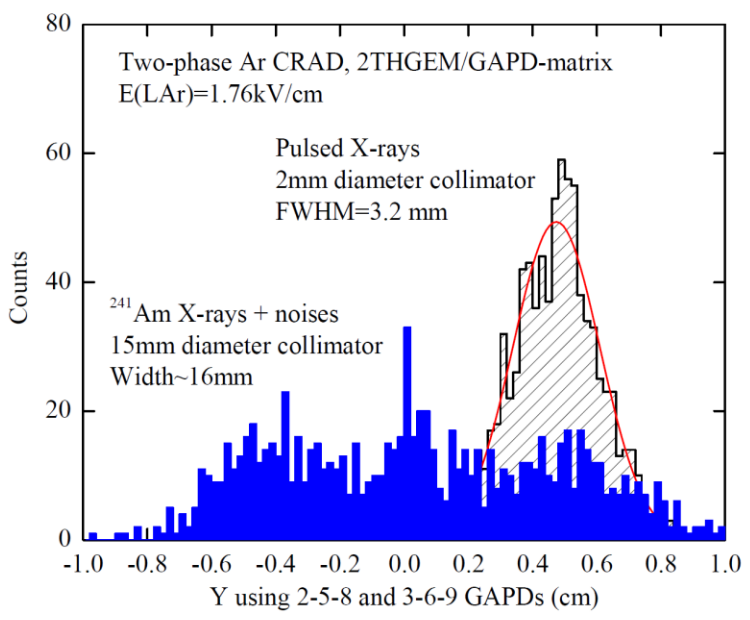
First demonstration of combined THGEM/GAPD-matrix readout in two-phase Ar CRAD [NIM A 732 (2013) 213]









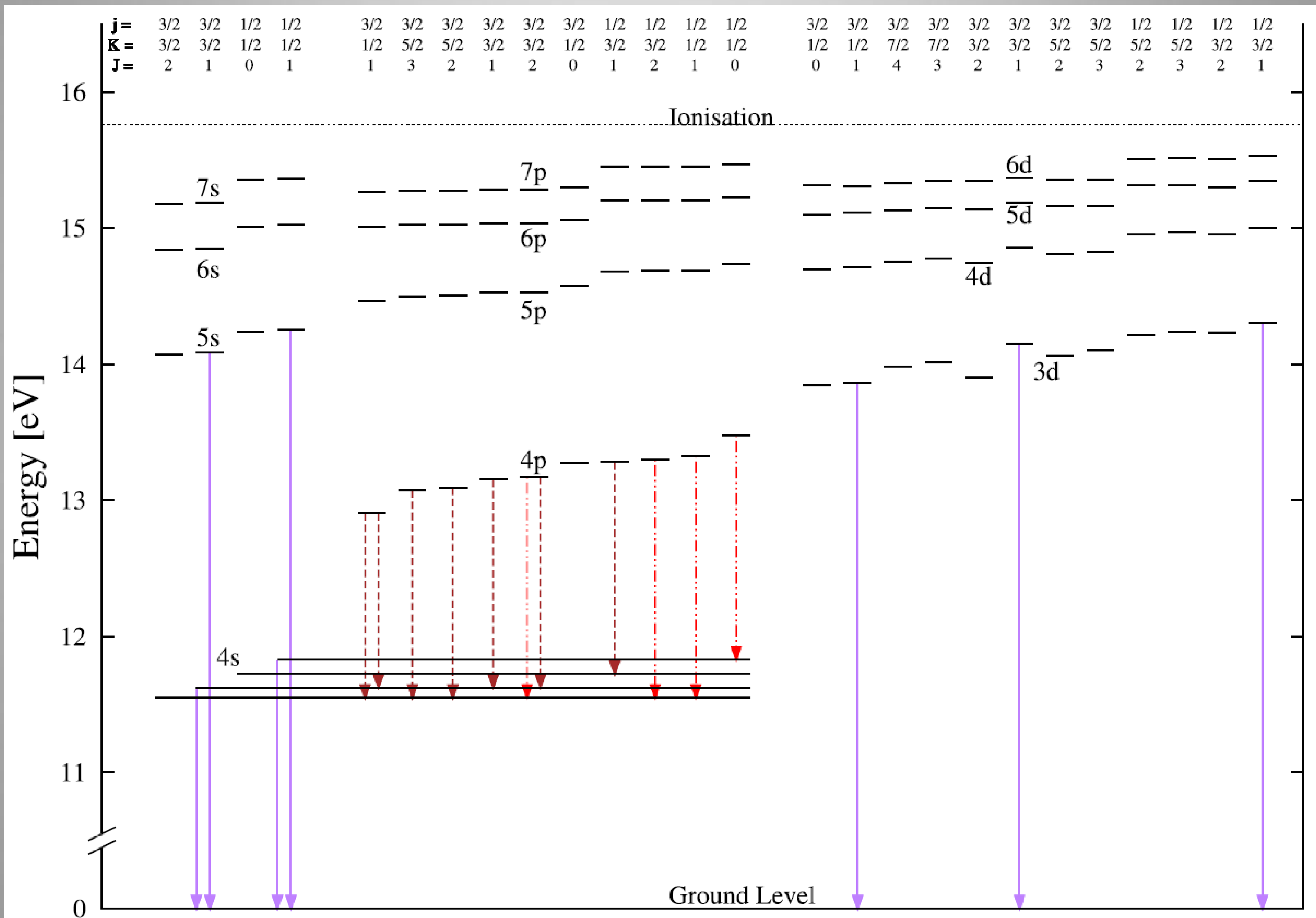


Spatial resolution of THGEM/GAPD-matrix readout is far superior compared to that of PMT-matrix: of the order of 1 mm, for deposited energy of 25 keV at charge (double-THGEM) gain of 160.

N_2 content measurement

After each cryogenic measurement, the Ar was liquified from the chamber back to a stainless steel bottle cooled with liquid nitrogen, so that the N_2 content remained constant throughout the entire measurement campaign. The latter lasted 5 months during which the setup (operated on a closed loop) was repeatedly evacuated but neither baked nor purified from N_2, resulting in a certain N_2 content established due to combined effect of the residual gas and internal outgassing in the bottle and cryogenic chamber. At the end of the campaign, the bottle with Ar was connected to a baked high-vacuum (10^{-9} mbar) system equipped with a Residual Gas Analyzer Pfeiffer-Vacuum QME220, where the N_2 content in Ar was measured in a flow mode at a pressure of 10^{-4} mbar: it amounted to 56±5 ppm. In the two-phase mode at 87 K, this value corresponds to the N_2 content of 56 ppm in the liquid and 151 ppm in the gas phase, according to "Raoult" law [28].

Ar energy levels



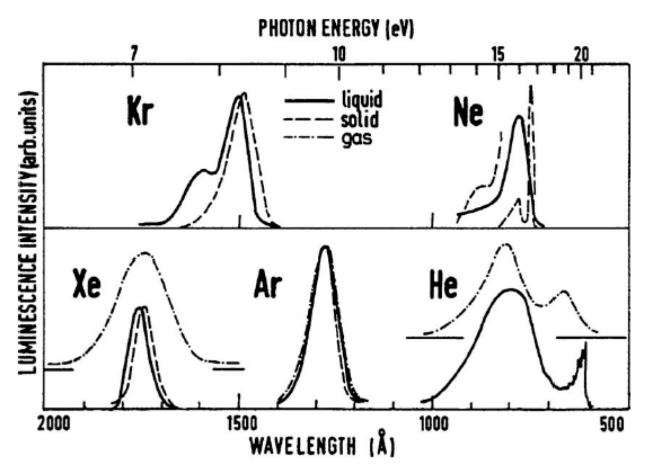
C.A.B. Oliveira et al. / Physics Letters B 703 (2011) 217–222

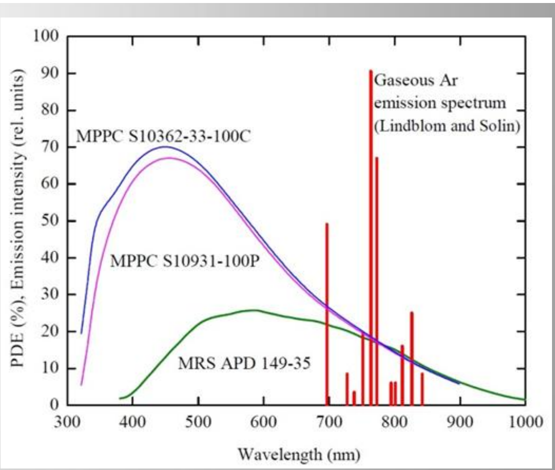
Proportional EL in two-phase Ar: basic mechanisms

the liquid-gas interface. In proportional electroluminescence the photon yield is basically proportional to the electric field, since the energy provided to the electrons by the electric field is almost fully expended in atomic excitations producing $Ar^*(3p^54s^1)$ and $Ar^*(3p^54p^1)$ states (the first one being metastable). These are followed by the photon emission in the Vacuum Ultraviolet (VUV), around 128 nm, due to excimer productions in three-body collisions and their subsequent decays [11–13]

$$Ar^*(3p^54s^1) + 2Ar \rightarrow Ar_2^* + Ar, \;\; Ar_2^* \rightarrow 2Ar + h\nu, \quad (1)$$

and by the photon emission in the Near Infrared (NIR), at 690-850 nm, due to $Ar^*(3p^54p^1) \rightarrow Ar^*(3p^54s^1) + h\nu$ atomic transitions [14–16]. The EL yield in the NIR is by an order of magnitude lower than that in the VUV, due to the higher excitation threshold [14, 16].





Ar excimer emission in VUV (around 128 nm):

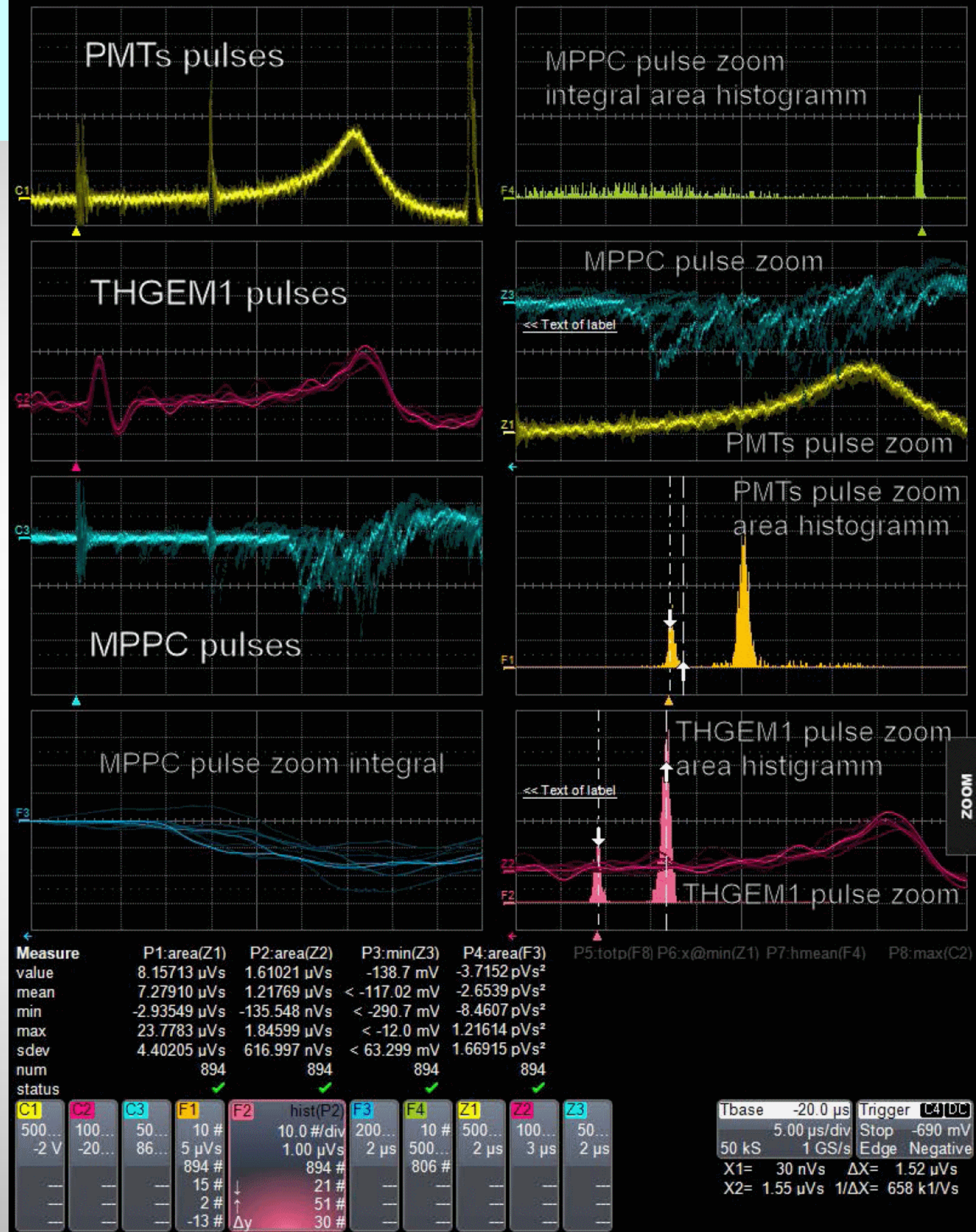
$$Ar^*(3p^54s^1) + 2Ar \rightarrow Ar_2^* + Ar$$

$$Ar_2^* \rightarrow 2Ar + h\nu$$

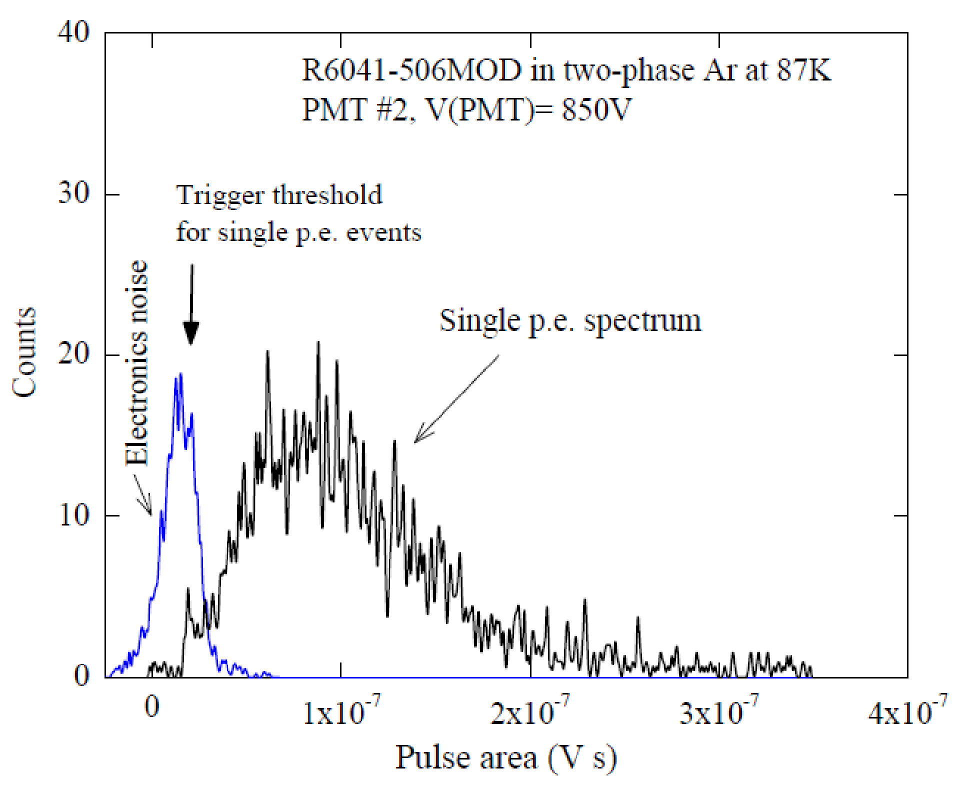
Ar atomic emission in NIR (690-850 nm):

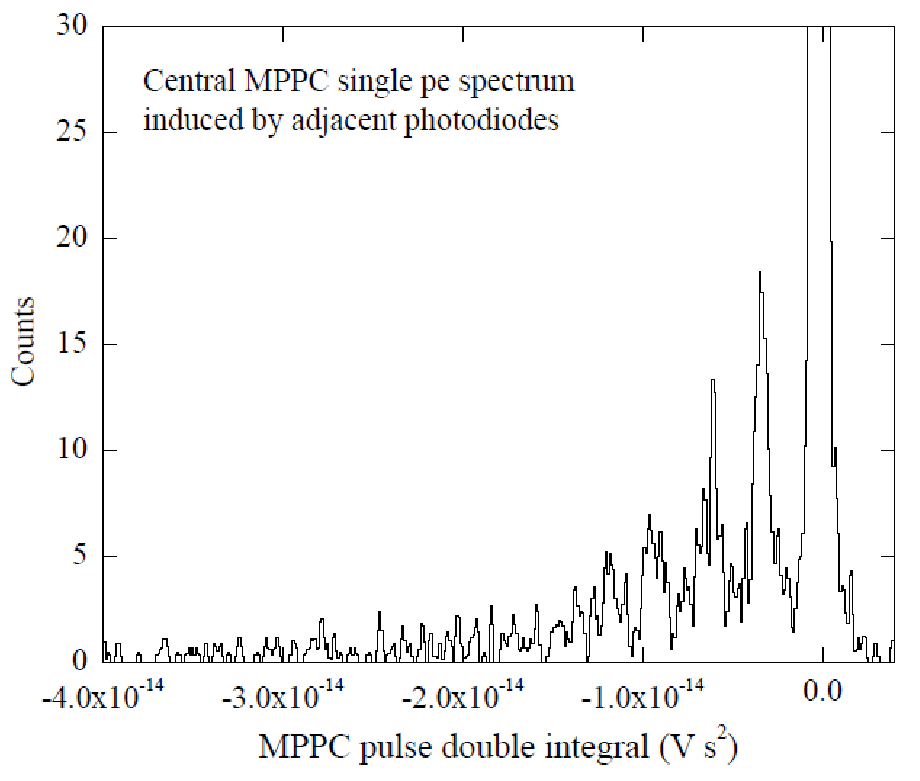
$$Ar^*(3p^54p^1) \rightarrow Ar^*(3p^54s^1) + h\nu$$

Experimental procedure

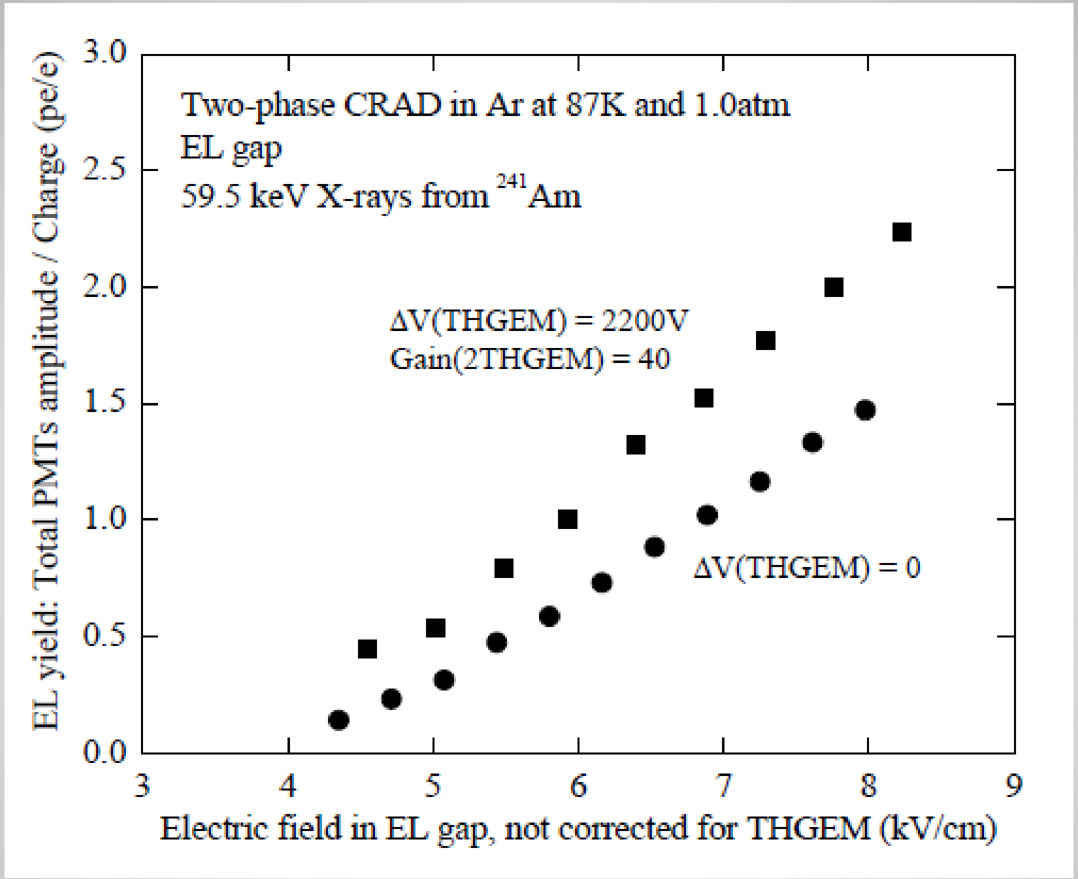


Cryogenic PMT and GAPD (MPPC) single pe spectra



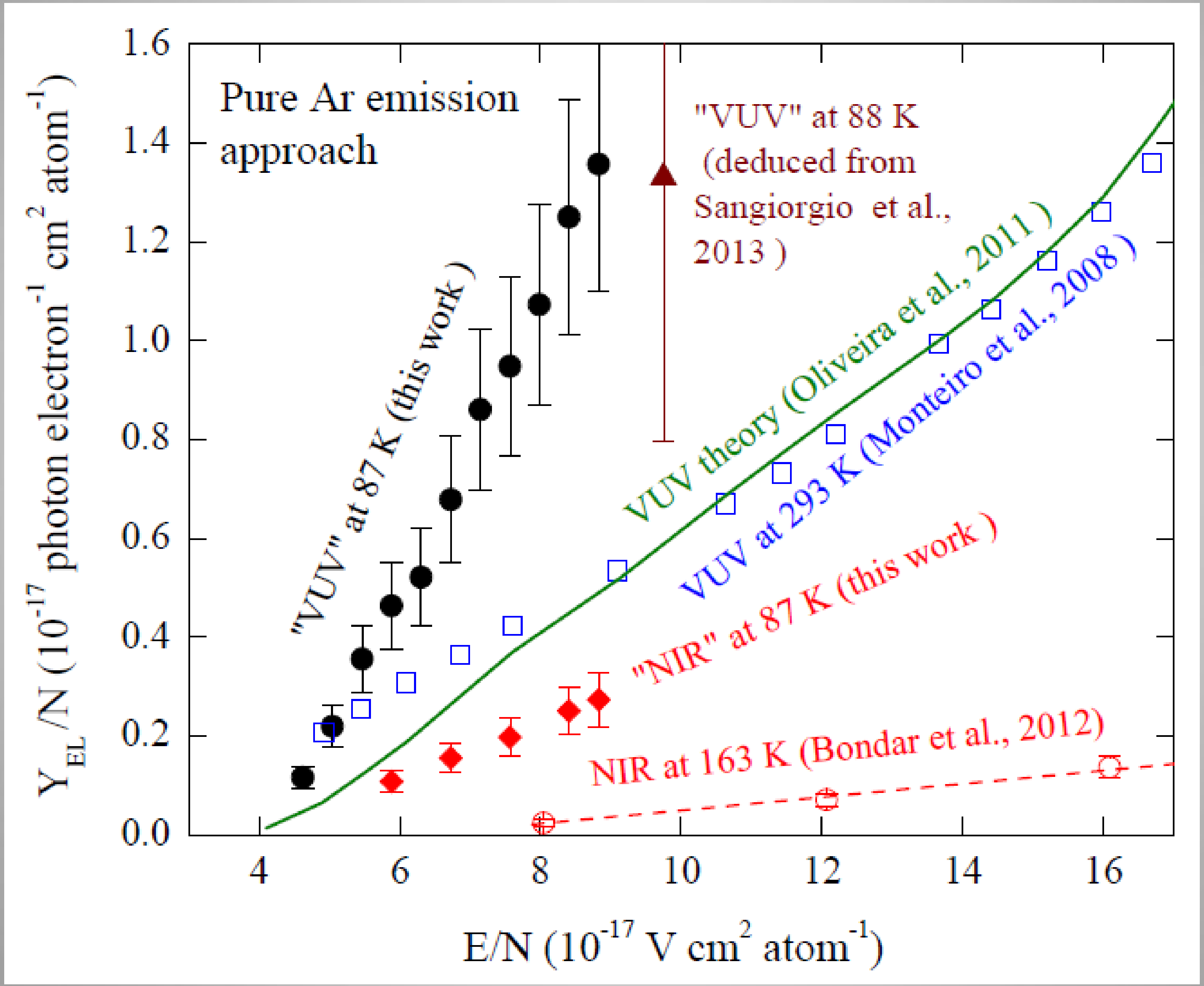


EL gap yield: effect of THGEM gain



EL gap yield is enhanced by a factor of 1.5 at double-THGEM gain of 40: presumably due to effect of high field extension from THGEM holes to EL gap.

"Pure Ar emission" approach in EL yield: wrong both in VUV and NIR!



Two-phase CRAD in Ar doped with N_2, with 9 l cryogenic chamber: ultimate sensitivity assessment

At the moment we have a sensitivity of 1.5 pe/e at 7 kV/cm (2.7 times more than expected in "pure Ar" approach)

Expected sensitivity enhancement:

- Adding more (100-200 ppm) N_2, fully converting VUV to UV: factor of 2
- Removing WLS and using UV acrylic: factor of 100/15%=6.7
- Doubling the number of PMTs or replacing those with MPPCs (200 pieces of 6x6 mm^2): factor of 2

This would result in 1.5*2*6.7*2= 40 pe/e: more than enough!