Measurement of ionization yields of nuclear recoils in liquid argon using two-phase detector

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Instrumentation for Colliding Beam Physics (INSTR-17)
March 1, 2017

Outline

1. Our global objectives and current activity

2. Description of a two-phase Cryogenic Avalanche Detector (CRAD)

3. Our recent results on ionization yields in liquid Ar

4. Future plans
- S1/S2 selection technique
- Neutron double scattering

5. Summary

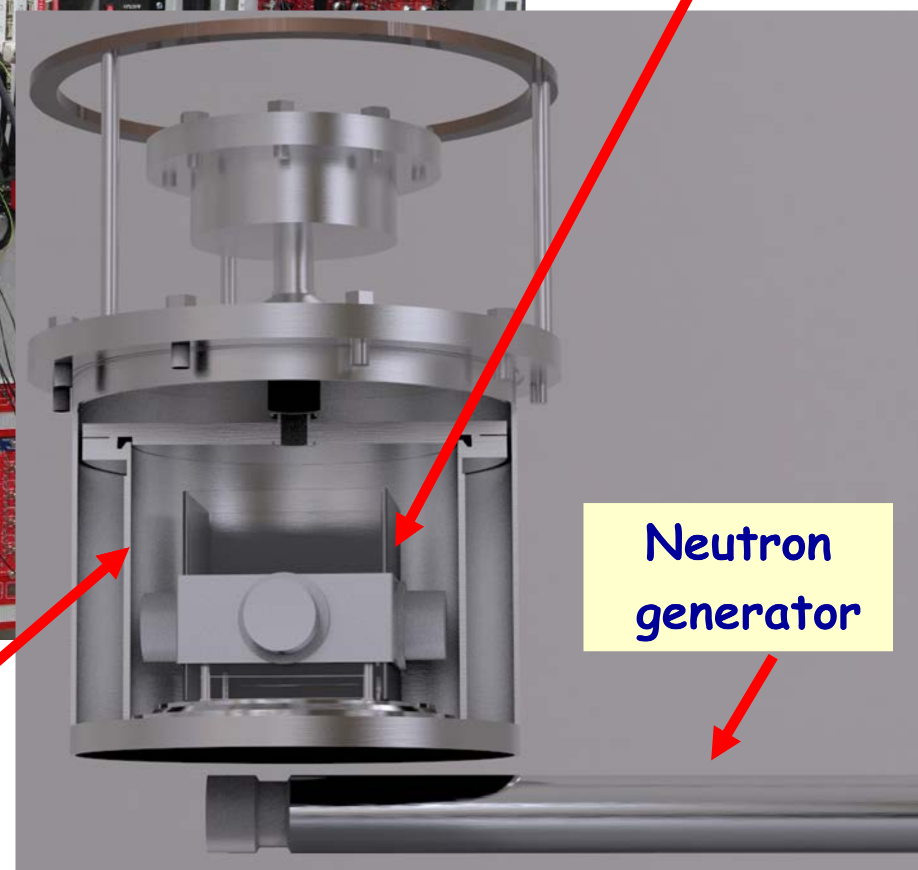
Our global objective and current activity

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

Our group is currently conducting researches in the following directions, in the frame of Laboratory of Cosmology and Elementary Particles (NSU and BINP) and in the frame of DarkSide experiment:

- Measurement of electroluminescence (EL) yields in two-phase Ar using a 9-liter detector.
- Problem of Ar doping with Xe and N2.
- Measurement of ionization yields of nuclear recoils in liquid Ar using neutron scattering technique.
- Development of new readout technique in two-phase Ar detectors using SiPM-matrices.

Experimental setup

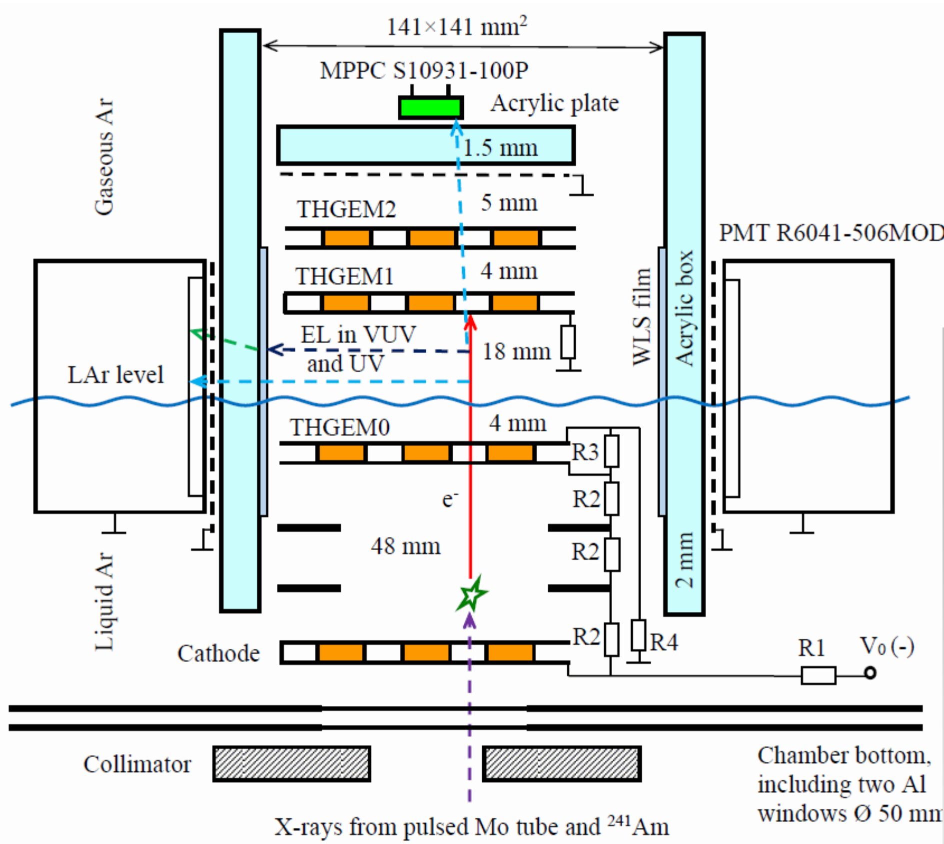


Assembly with EL gap and PMT readout

Neutron generator

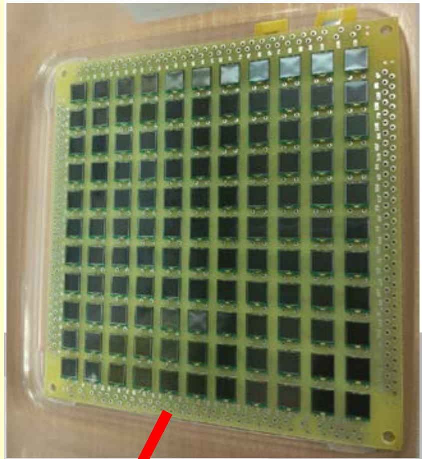
A vacuum-insulated 9-liter two-phase cryogenic chamber filled with 2.5 liters of liquid Ar

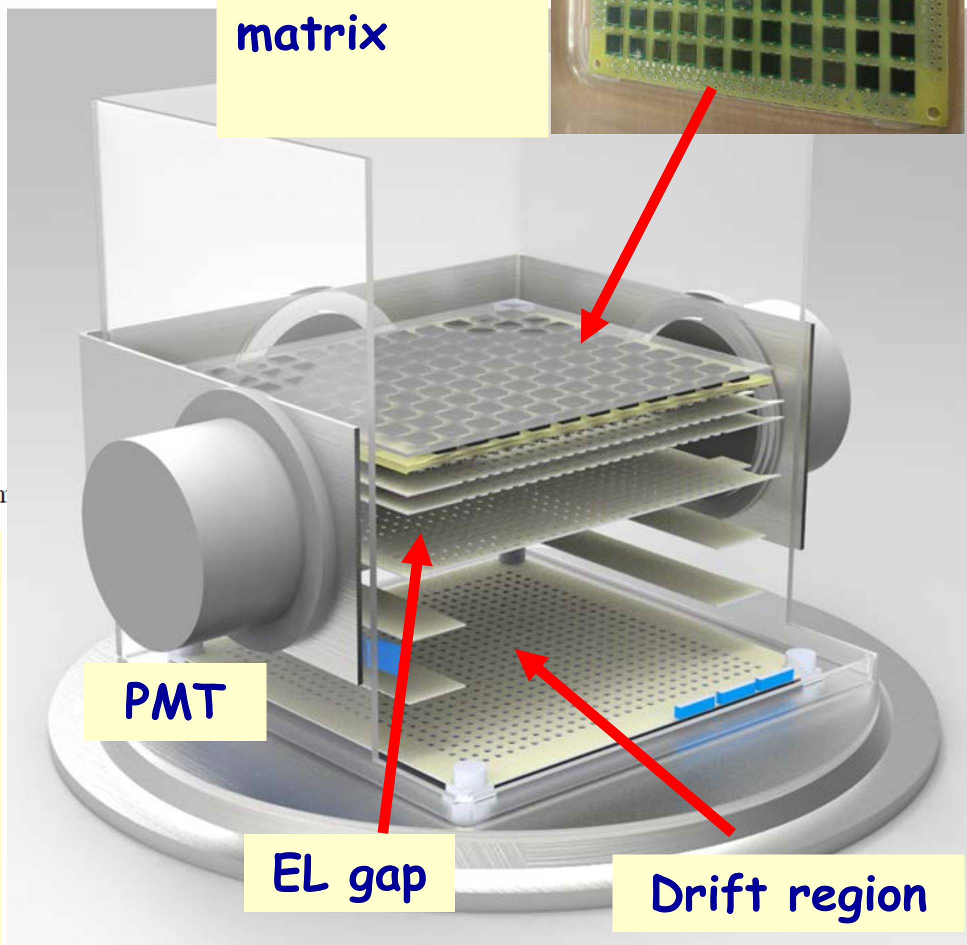
Cryogenic chamber



Hamamatsu S13360-6050PE

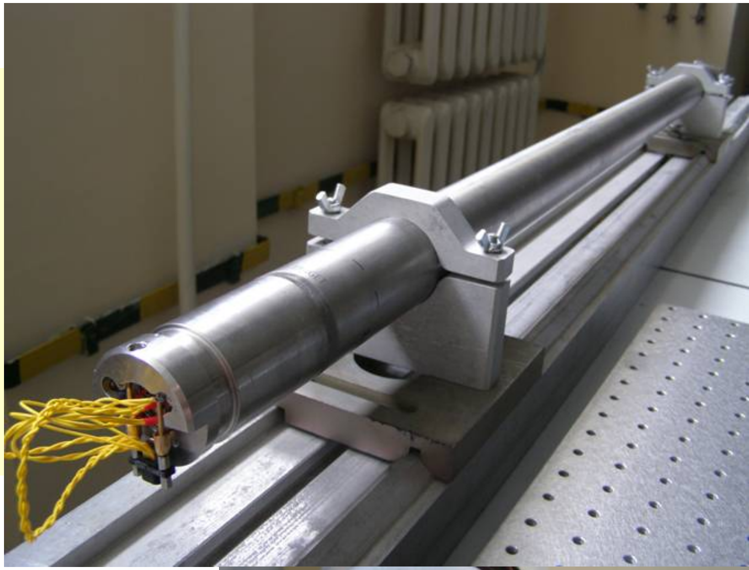
- 6x6 mm^2
- 11x11 matrix





The cryogenic chamber included a cathode electrode, two field-shaping electrodes, a THGEM0, immersed in liquid Ar layer and a double-THGEM assembly, consisting of a THGEM1 and THGEM2, placed in the gas phase above the liquid.

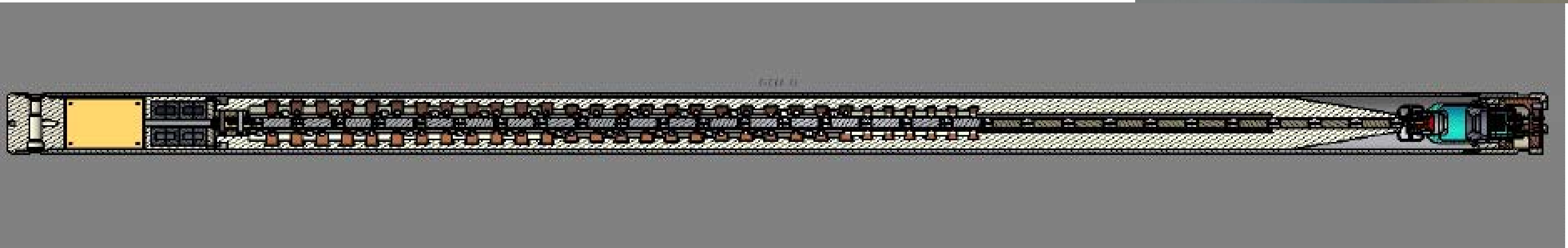
Neutron generator produced in BINP



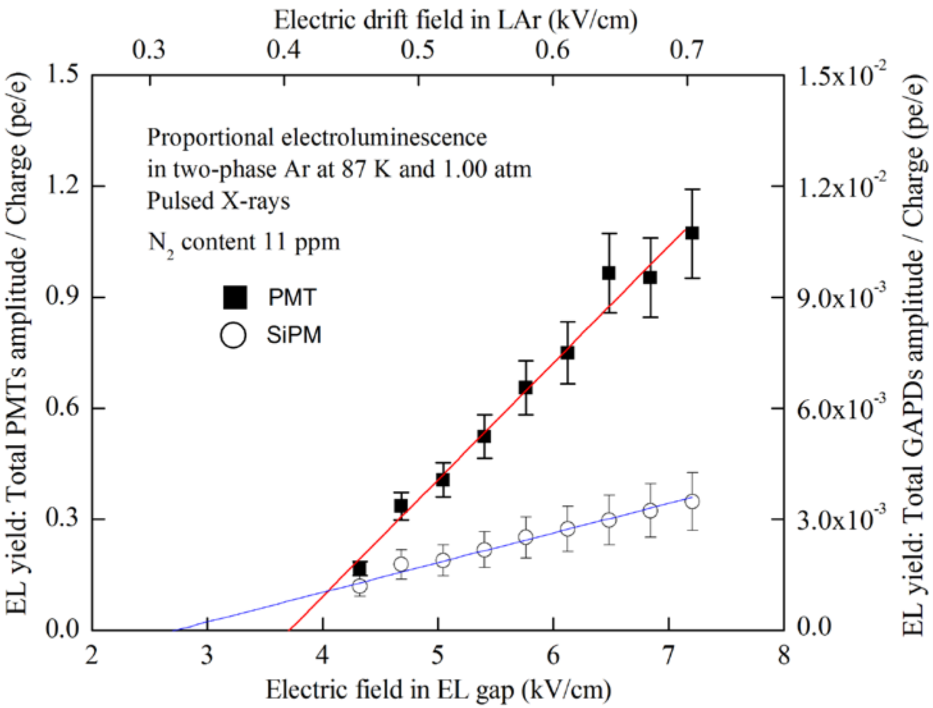
To produce neutrons, a specially designed neutron generator was used that continuously emitted monoenergetic not collimated neutrons with a kinetic energy of 2.45 MeV obtained in the DD fusion reaction.

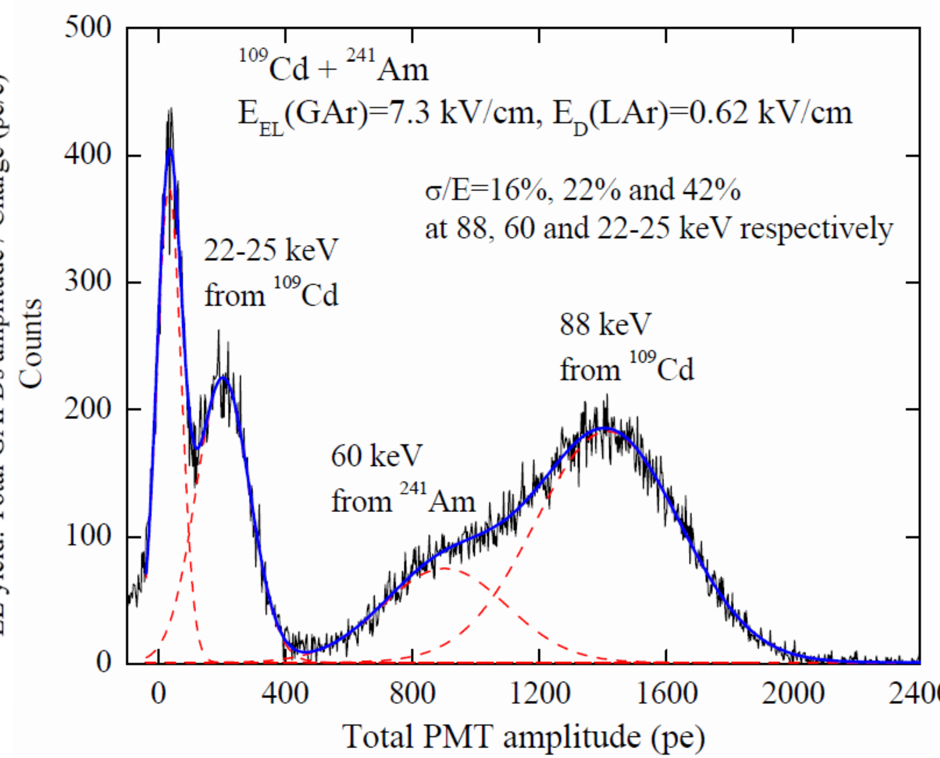
The design parameters:

- **Neutron yield: 10^5 neutrons/s**
- **Nominal current of ions: 50 uA**
- **Operating voltage: 80 kV**
- **Insulation: SF_6, 8 atm**



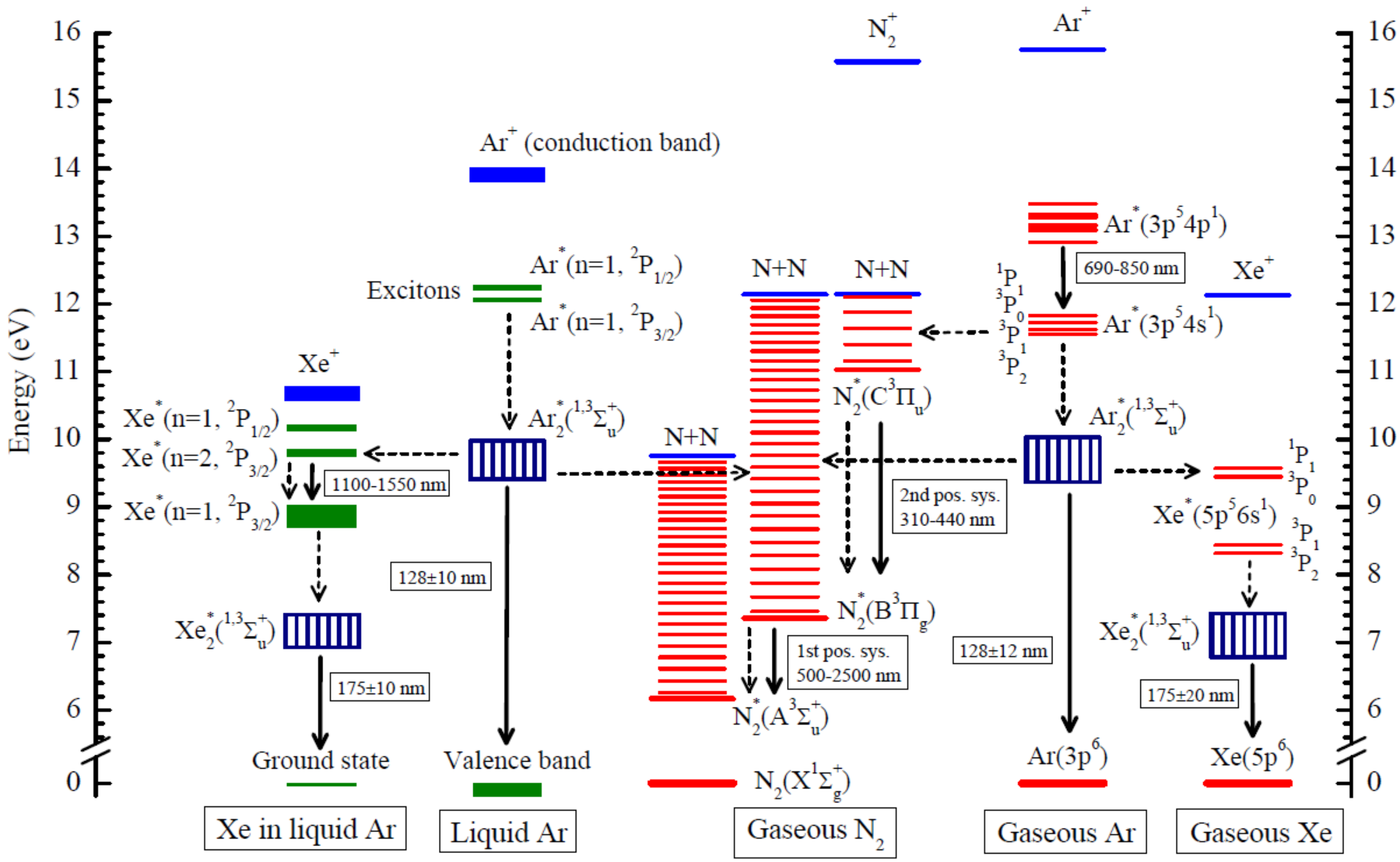
Study of proportional EL in two-phase Ar: EL yields and amplitude spectra





- The EL gap yield as a function of the electric field in the gap, measured using PMT or SiPM signals. The amplitude spectrum of the total PMT signal from the EL gap induced by X-ray from a mixture of the Cd and Am radioactive sources.
- High EL gap yield of 15 pe/keV (1 pe/e) and good energy resolution of 22% at 60 keV have been reached at an electric field of 7 kV/cm in the EL gap.

The problem of doping Ar with Xe and N2

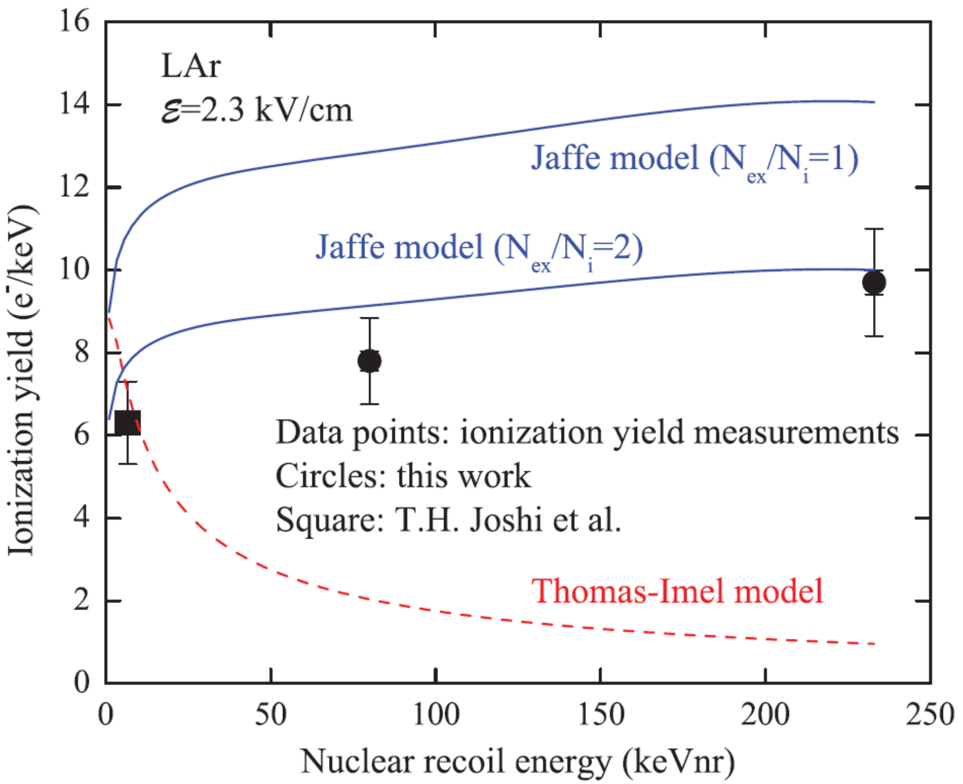


- Photon emission and atomic collision processes in two-phase argon doped with xenon and nitrogen: the most complete compilation over past 50 years (A. Buzulutskov, Eprint 1702.03612).
- The problem is currently under study in our group. You can find details in the article.

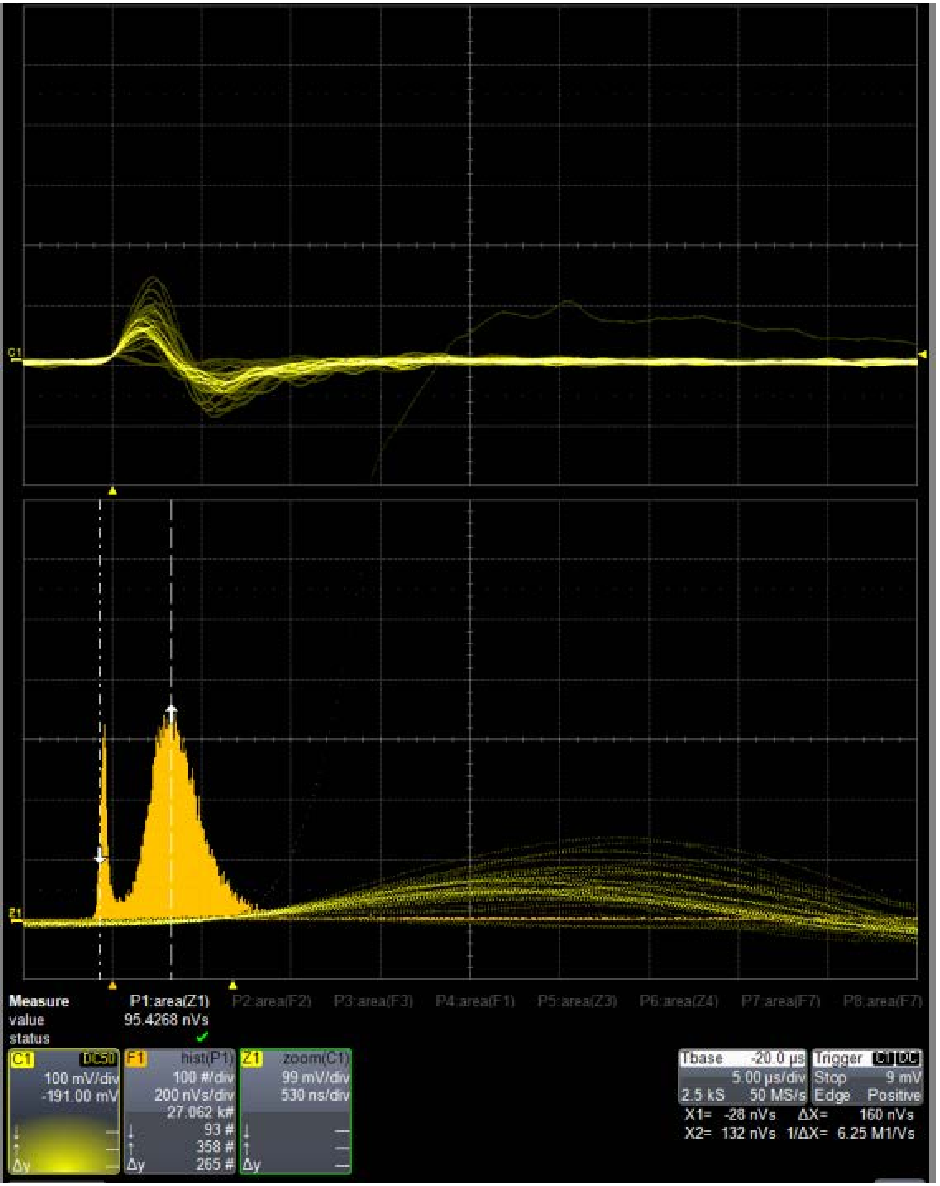
Ionization yield

- A particle interaction in the liquid phase produces primary scintillation (S1) and ionization.
- The electrons are drifted away from the interaction site by an electric field and extracted into the gas where they create secondary scintillation (S2).
- The ionization yield is the ratio of the number of electrons escaping recombination with positive ions (ne) and the energy deposited by a nuclear recoil (E).
- Recently we have measured ionization yields of nuclear recoils in liquid argon at 80 and 233 keV (EPL, 108 (2014) 12001)
- In present work the ionization yield of nuclear recoils in liquid Ar has been measured at high energy 233 keV for several electric fields.

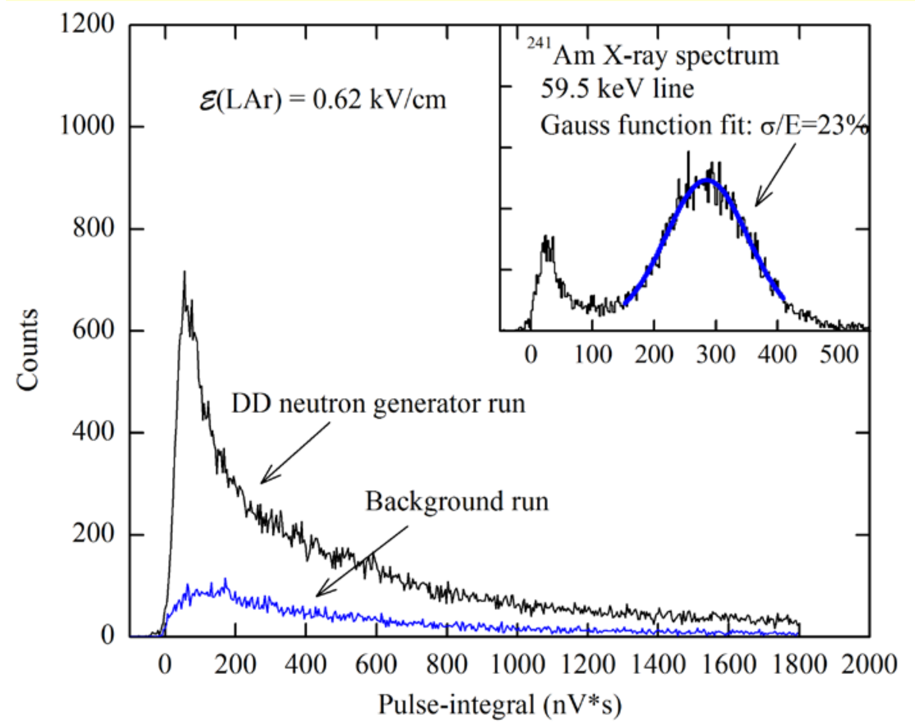
$$Q_y(E,\mathcal{E})\,[e^-/keV] = n_e(E,\mathcal{E})/E$$



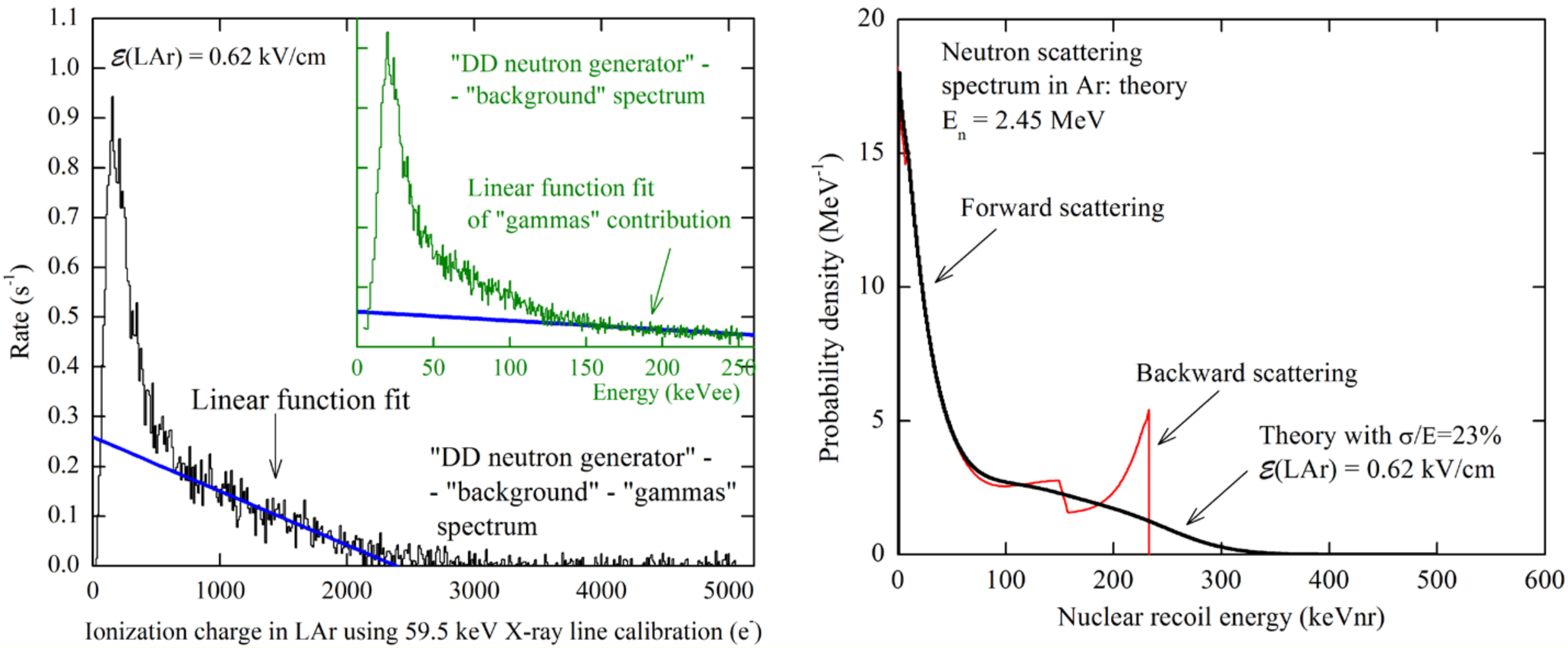
Measurement of ionization yield: raw signals



- The primary ionization charge in liquid Ar was produced by either 60 keV gamma from 241Am or 2.45 MeV neutron from the DD-generator.
- A typical oscillogram with a raw signal and an integral spectrum for Am isotope.
- The integral spectra for Am, neutron and background runs.



Measurement of ionization yield: experimental and theoretical spectra

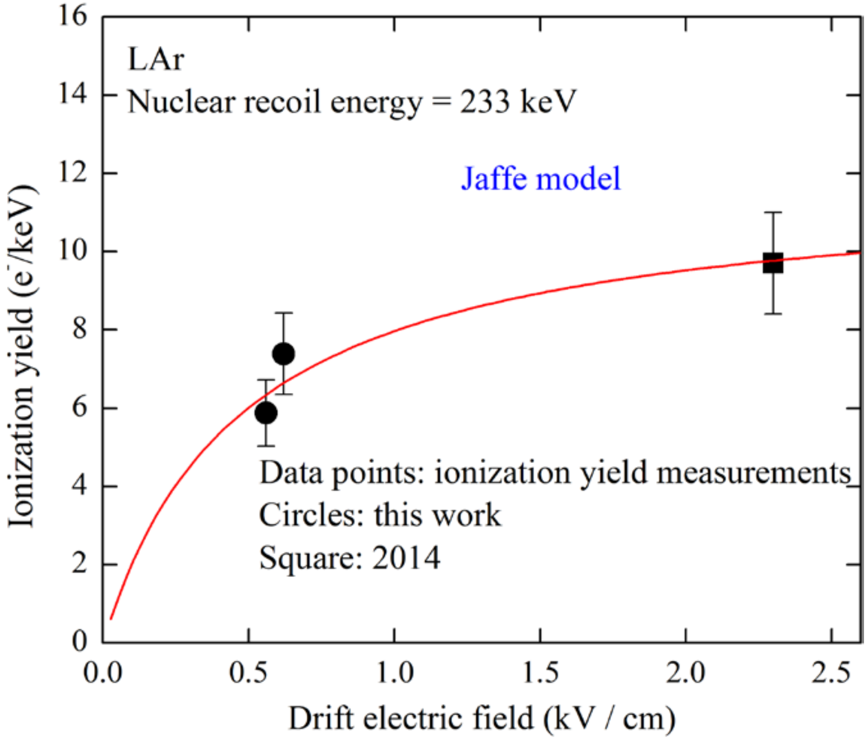


To measure the ionization yield we subtracted the background-run contribution from the neutron run. After this we subtracted the gamma-ray contribution, resulting from a radiative capture in surrounding materials. Finally, the pulse integral was normalized to that of 60 keV peak and we found a spectrum end-point in units of ne.

The theoretical spectrum was convolved with an energy resolution function.

The ionization yield was calculated by dividing the end point of experimental spectrum to the theoretical one.

Measurement of ionization yield: results



Jaffe model

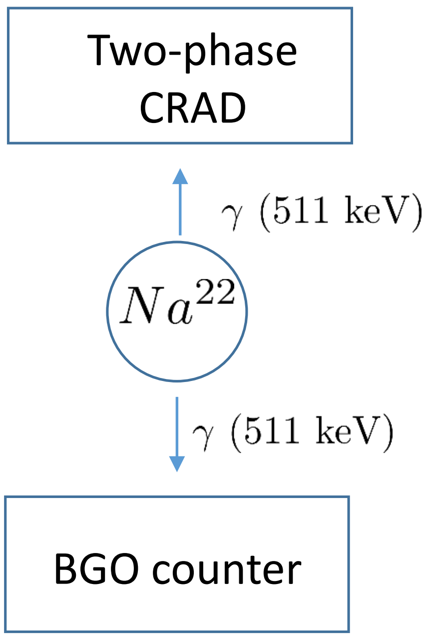
$$Q_y = \frac{A}{1+B/\mathcal{E}}$$

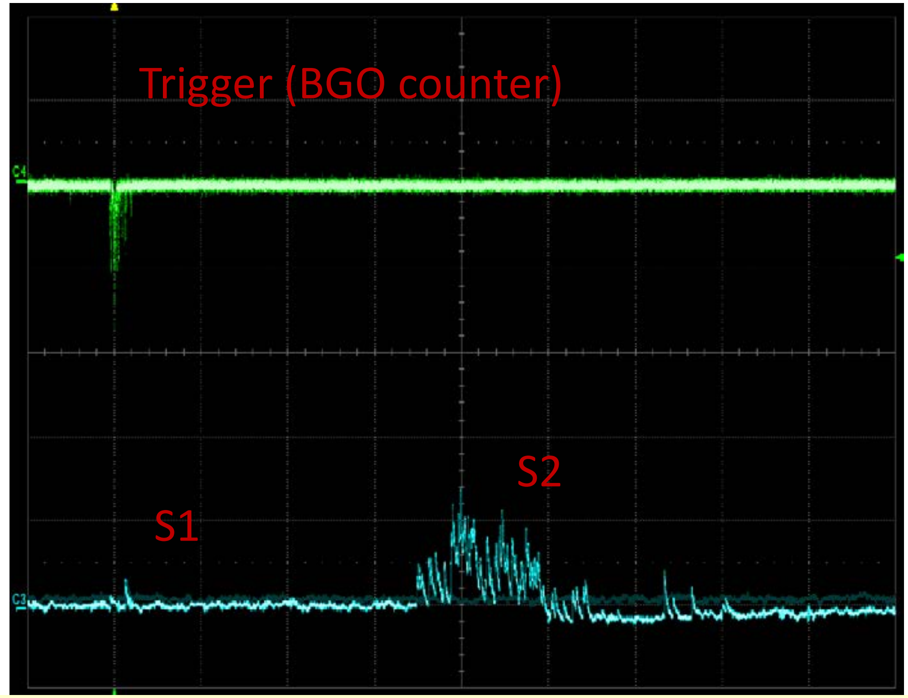
Ionization yield:
5.9 +- 0.8 and 7.4 +- 1 e-/keV at 0.56 and 0.62 kV/cm

A field dependence is well described by Jaffe model (red curve).

A systematic error is dominant and occurs because of using liquid Ar ionization yield of electron recoil for calibration.

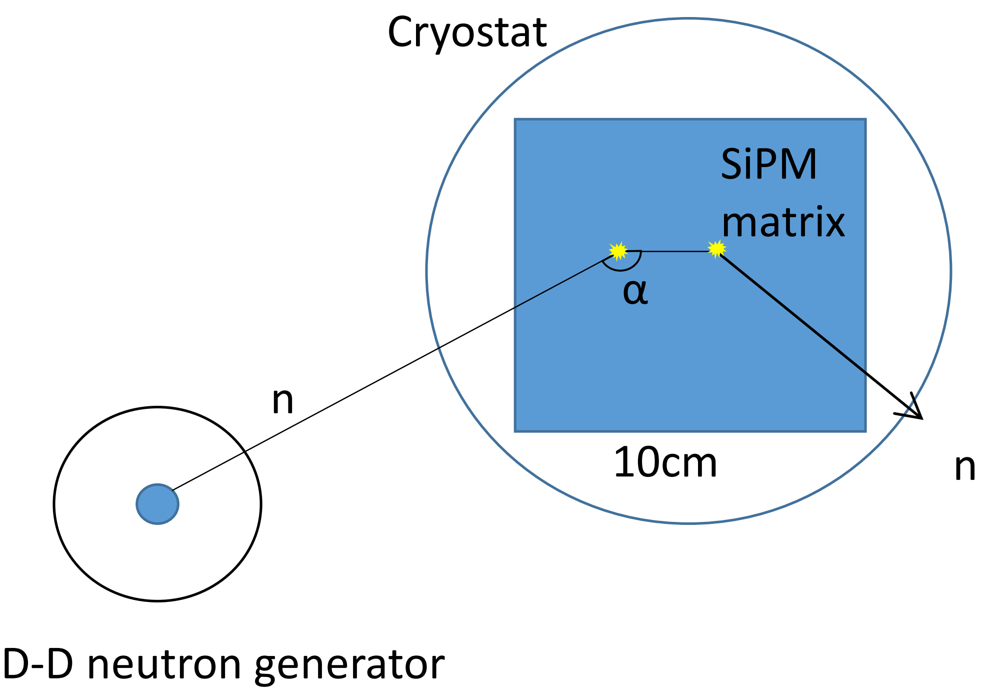
Towards nuclear recoil selection using S1/S2 signals





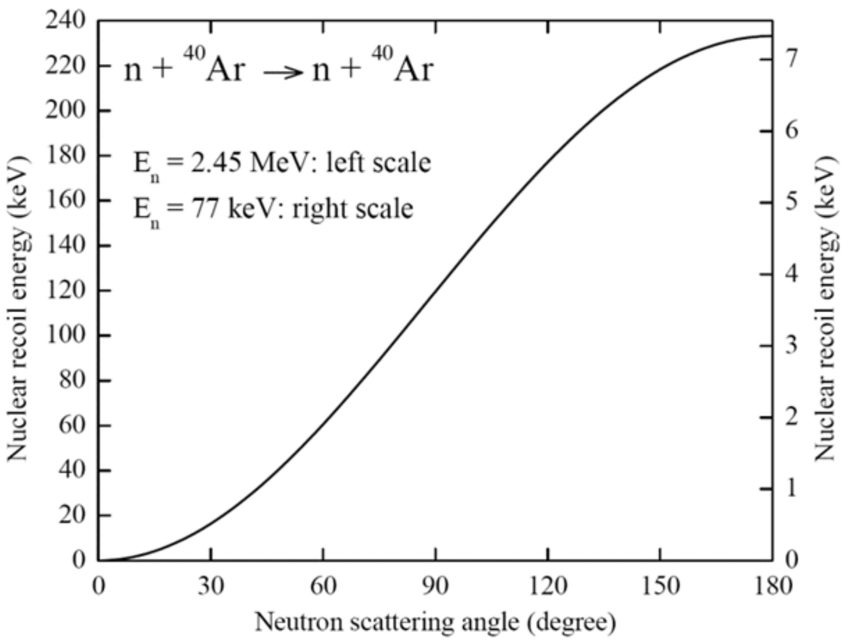
- Previously we used spectra subtraction to reject background events, but there is also opportunity to use S2 / S1 as discriminator factor for nuclear and electron recoil.
- We irradiated Cryogenic Avalanche Detector by 22Na isotope, which produce two gamma quanta. One of them was detected by BGO counter and produced trigger and another one was detected by CRAD.
- Unfortunately, S1 signal is low, so we plan to install additional SiMP matrix on the detector bottom and improve light collection.

Neutron double-scattering concept for low-energy calibration in LAr



The double-scattering concept has been recently realized in LXe in LUX experiment [arXiv:1608.05381]

Recoil energy dependence as a function of the neutron scattering angle



Having high spatial resolution, of 1 mm, we expect reaching accuracy of about 2° in scattering angle, corresponding to nuclear recoil energy as low as a few keV.

Summary

- We have measured the ionization yields of nuclear recoils in liquid Ar using neutron scattering technique, in new ranges of energies and electric fields.

- Neutron double-scattering technique, for low-energy calibration of liquid Ar dark matter detectors, is being developed in our lab.

- We continue to study proportional electroluminescence in two-phase Ar. In particular, we are trying to resolve the problem of doping Ar with Xe and N2 in the two-phase mode.

- These studies are conducted in the frame of R&D program for the DarkSide dark matter search experiment.

Backup slides

Photon emission and atomic collision processes in two-phase argon doped with xenon and nitrogen

–We present a comprehensive analysis of photon emission and atomic collision processes in two-phase argon doped with xenon and nitrogen. The dopants are aimed to convert the VUV emission of pure Ar to the UV emission of the Xe dopant in the liquid phase and to the near UV emission of the N2 dopant in the gas phase. Such a mixture is relevant to two-phase dark matter and low energy neutrino detectors, with enhanced photon collection efficiency for primary and secondary scintillation signals.

Based on this analysis, it is shown that Xe dopant may successfully perform its job on VUV-to-UV conversion in the liquid phase even in presence of N2 impurity, if its content does not exceed 50 ppm.

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).

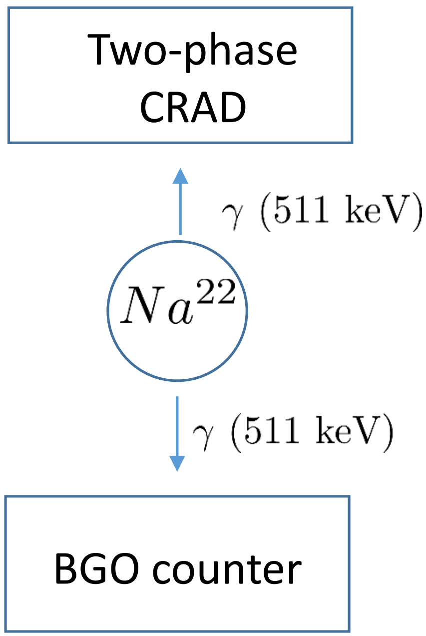
Also, we have recently joined DarkSide20k collaboration.

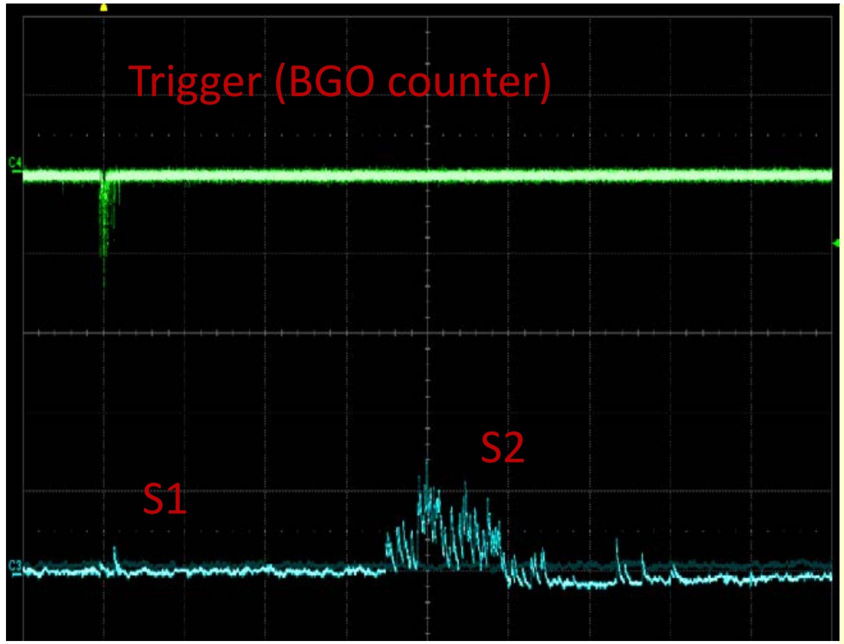
Group management:
A. Buzulutskov (leader), A. Bondar (deputy director of BINP and dean of Physics Department of NSU), A. Dolgov (head of LCEP).

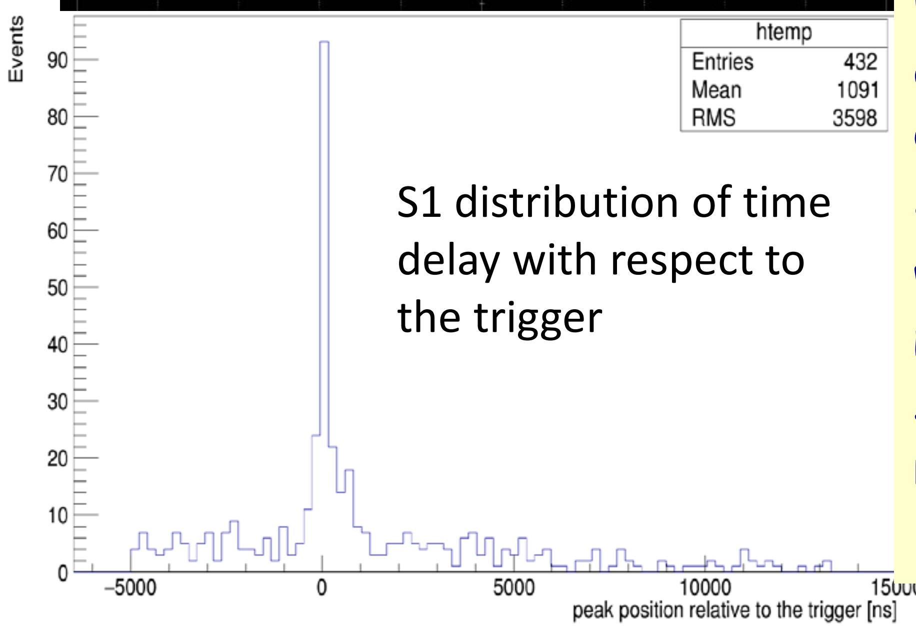
Group members:
A. Sokolov (senior scientist), L. Shekhtman (leading scientist), V. Nosov (engineer), R. Snopkov (engineer), E. Shemyakina (PHD student), V. Oleinikov (PHD student), A.Chegodaev (technician).

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

Towards nuclear recoil selection using S1/S2 signals



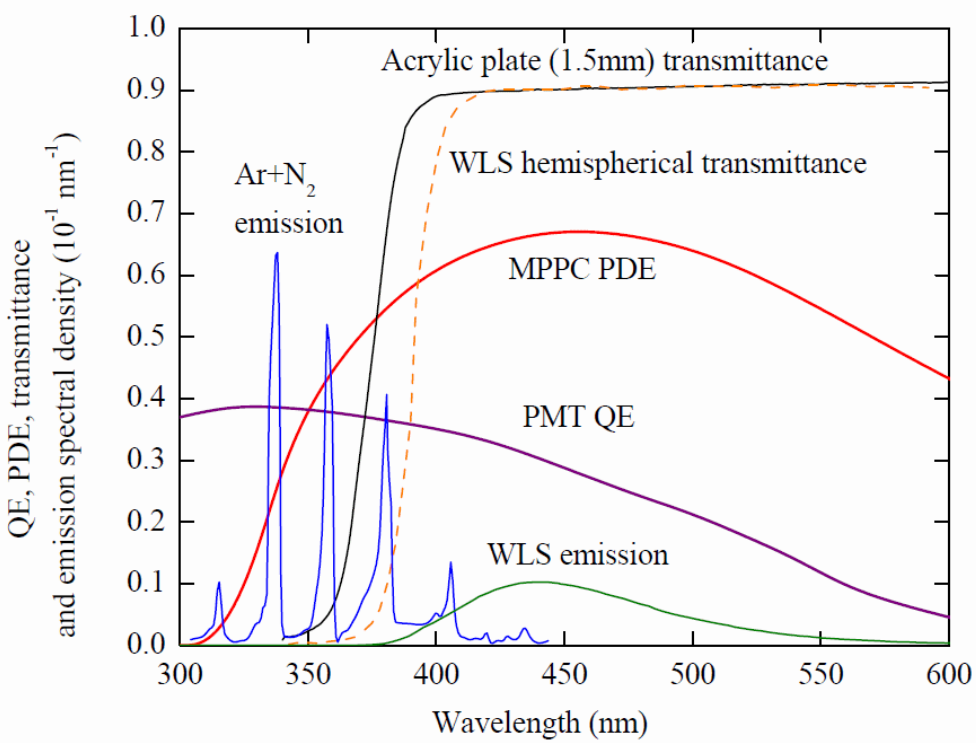


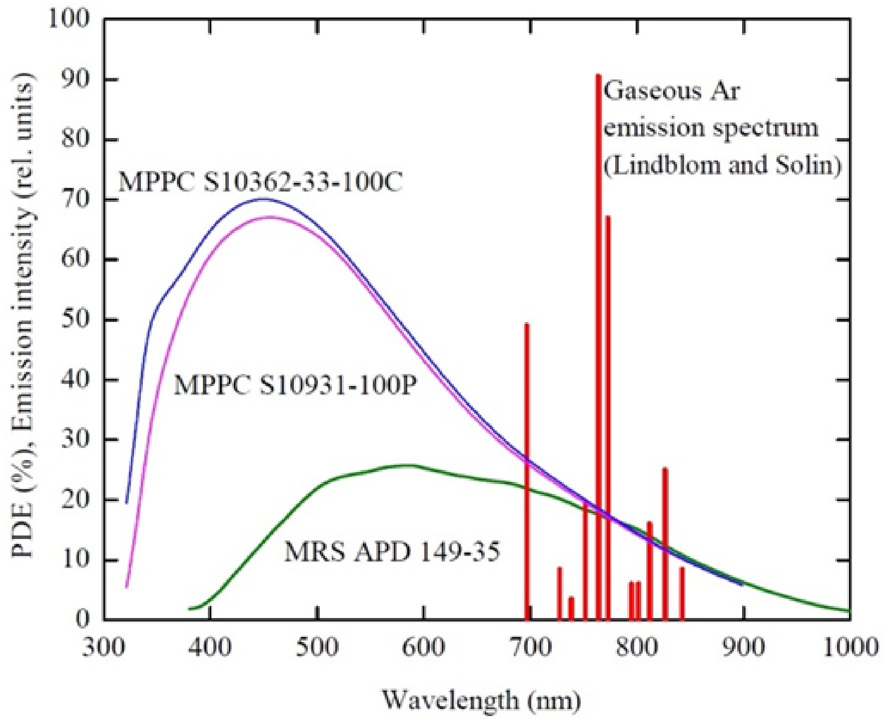


S1 distribution of time delay with respect to the trigger

- We irradiated Cryogenic Avalanche Detector by sodium 22 isotope, which produce two gamma quanta.
- One of them was detected by BGO counter and produced trigger and another one by CRAD.
- On this spectrum we clearly see peak near trigger time, so signals were really from sodium 22 isotope.

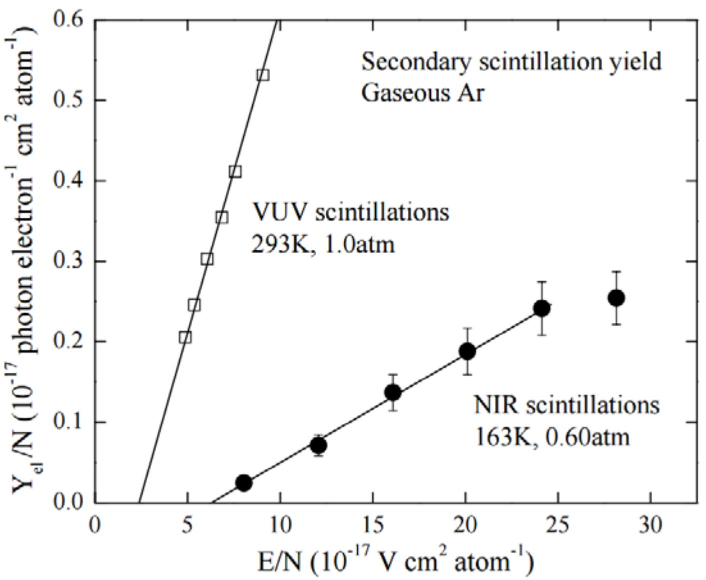
Optical spectra



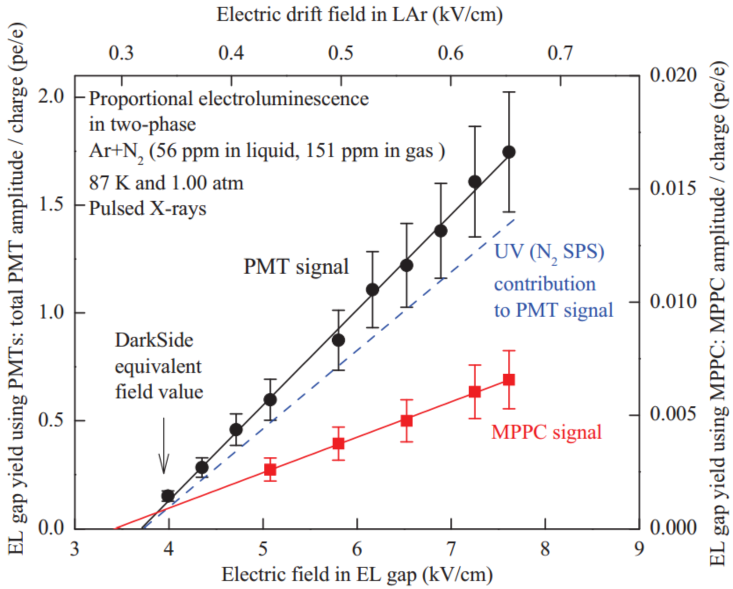


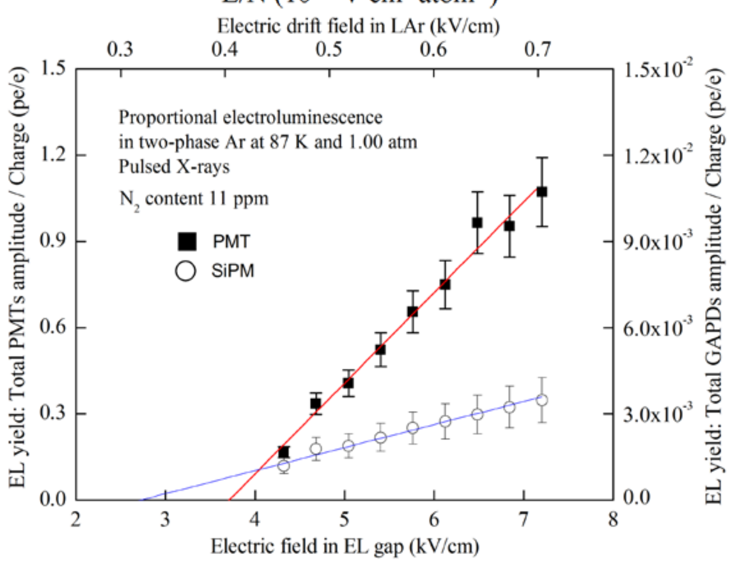
Resolving problem of EL yield is in the progress.

EPL, 94 (2011) 52001



EPL, 112 (2015) 19001





Current result

Ionization yield

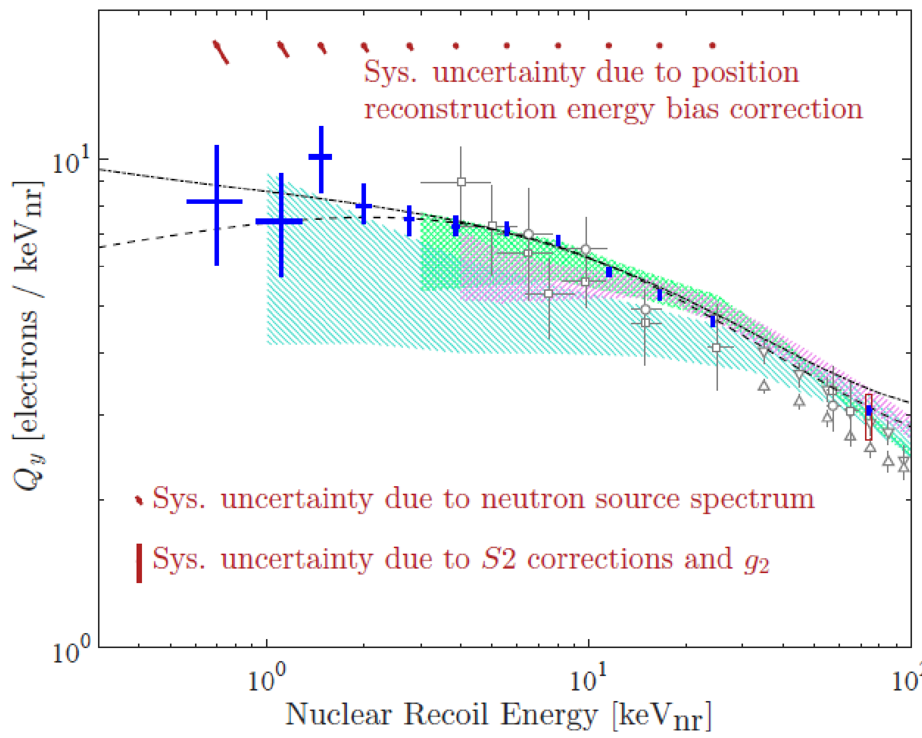
$$Q_y(E,\varepsilon) = n_e(E,\varepsilon)/E$$

(LXe): 0.7 – 100 keVnr

SCENE experiment (LAr): 17 – 57 keVnr, but in [PE/keVnr]

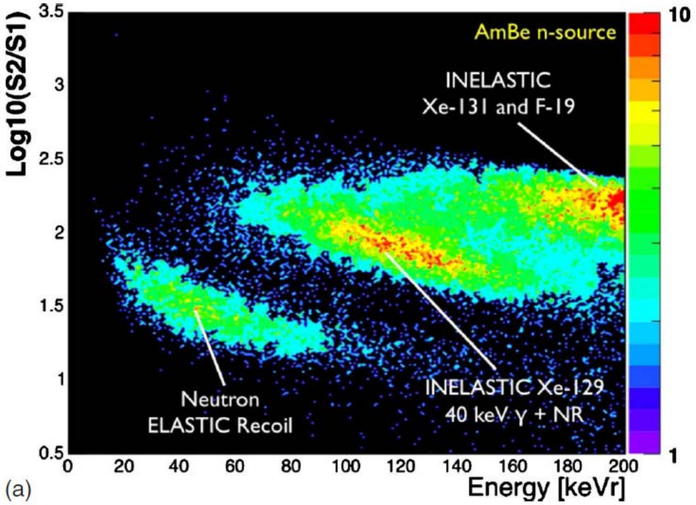
TABLE VII. Q_y values in units of [PE/keV] with total combined errors.

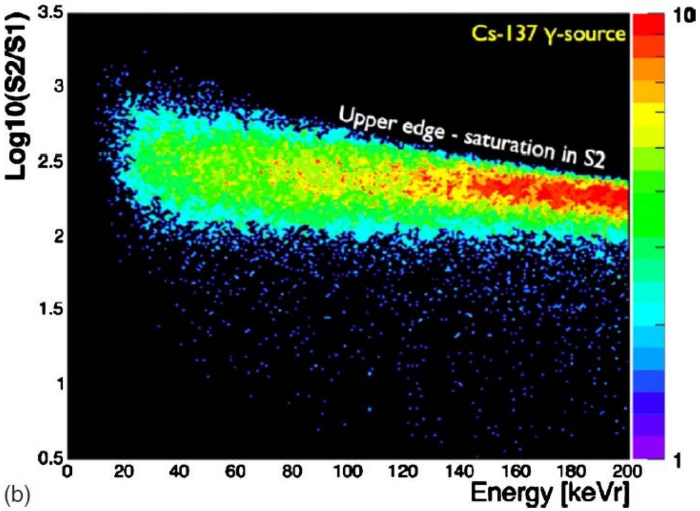
Drift field [V/cm]	Recoil energy [keV] 16.9	25.4	36.1	57.3
96.4	9.3 ± 0.6			4.4 ± 0.4
193	11.4 ± 0.6	9.3 ± 0.5	7.6 ± 0.4	5.7 ± 0.3
293	13.1 ± 0.8	10.7 ± 0.6	8.7 ± 0.5	6.4 ± 0.4
486	14.5 ± 0.7	12.0 ± 0.6	9.8 ± 0.4	7.3 ± 0.5



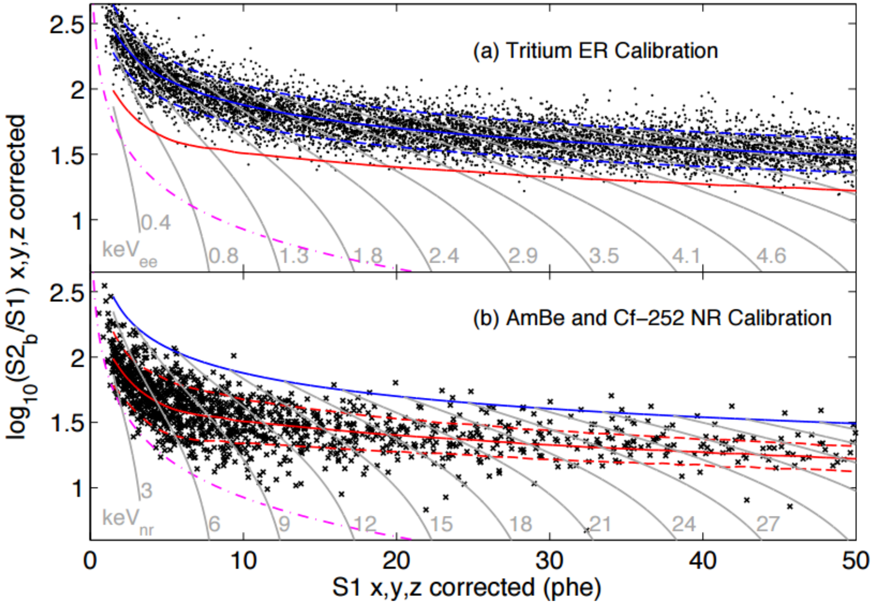
S1 / S2 separation in LXe

XENON experiment

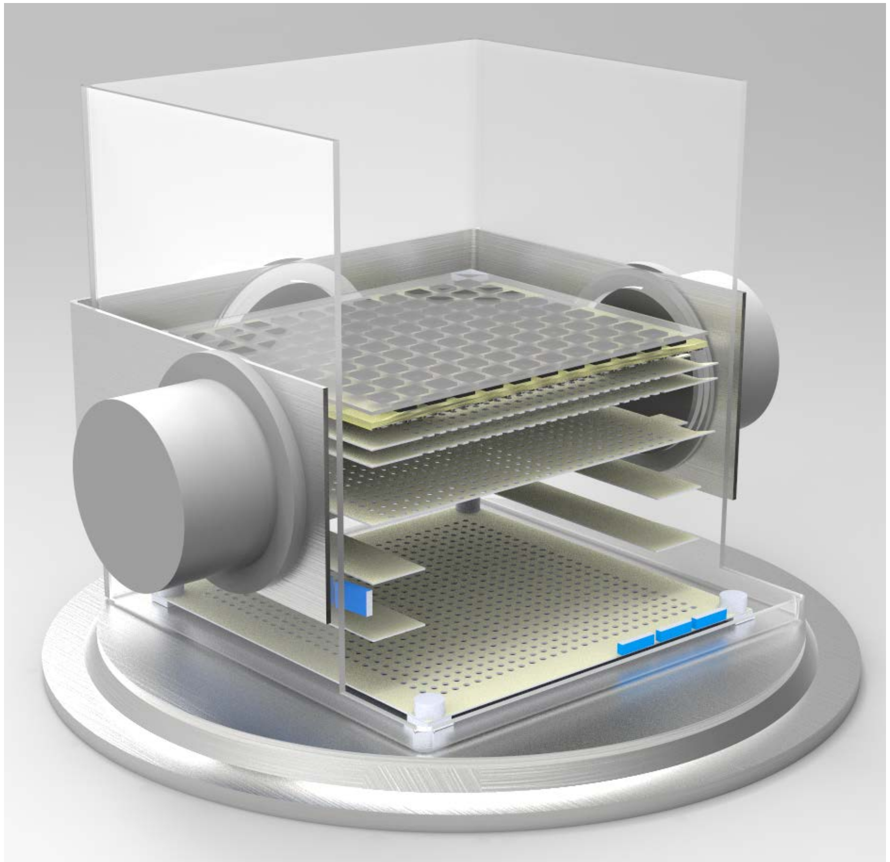


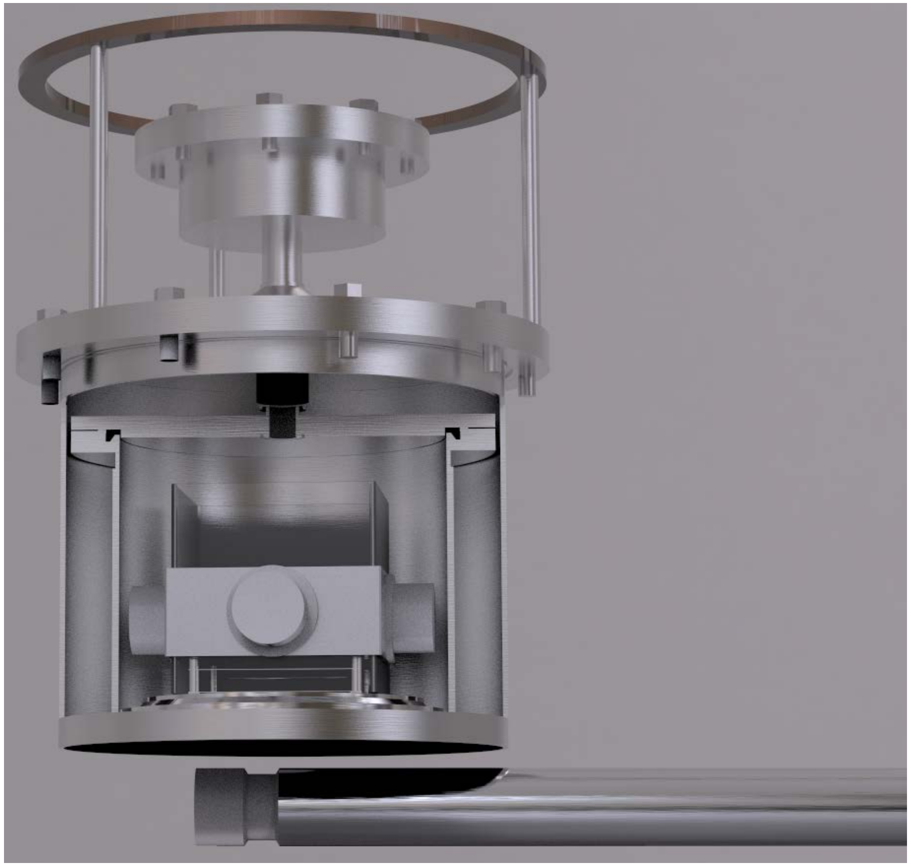


LUX experiment



Chamber 3D - view

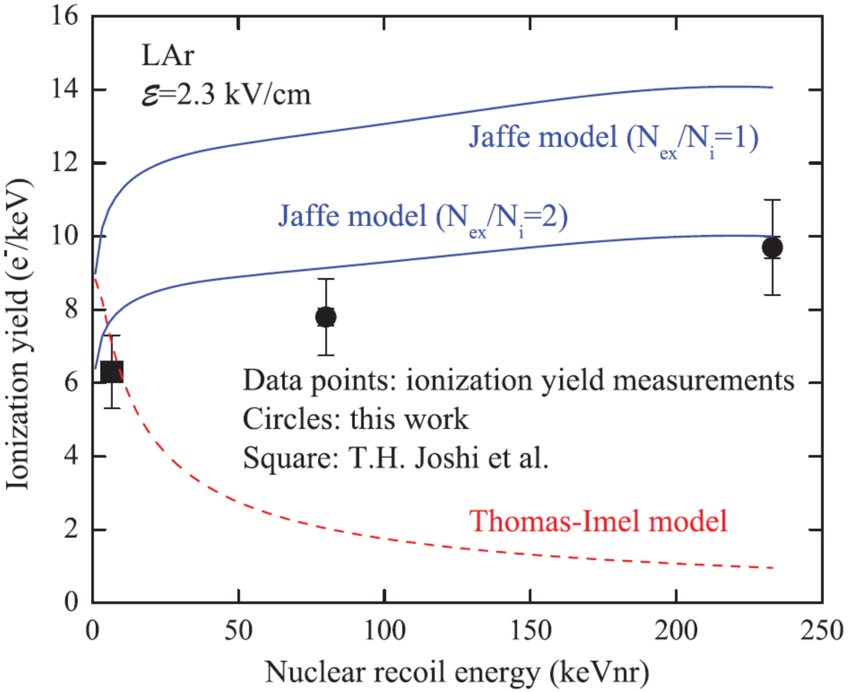




Ionization yield

$$Q_y(E,\varepsilon)\,[e^-/keV] = n_e(E,\varepsilon)/E$$

Our previous results
EPL, 108 (2014) 12001



SCENE experiment

PHYSICAL REVIEW D **91**, 092007 (2015)

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Phys. Rev. Lett., 112 (2014) 171303, 6.7 keVnr

TABLE II. Measured ionization yields with uncertainties.

$\mathcal{E}$ (V/cm)	Q_y (e^-/keV)	Statistical	Systematic
240	3.6	$^{+0.1}_{-0.1}$	$^{+0.5}_{-1.1}$
640	4.9	$^{+0.1}_{-0.2}$	$^{+0.6}_{-1.2}$
1600	5.9	$^{+0.2}_{-0.2}$	$^{+0.7}_{-1.4}$
2130	6.3	$^{+0.1}_{-0.3}$	$^{+0.8}_{-1.6}$

Ionization yield

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- In present work the ionization yield of nuclear recoils in liquid Ar has been measured at high energy 233 keV for several eclectic fields.

Recently we have measured ionization yields of nuclear recoils in liquid argon at 80 and 233 keV (EPL, 108 (2014) 12001)