Antineutrino Detector Development for Safeguards in Russia

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Activity was started 30 years ago in Kurchatov Institute.

1974-1977

It was shown that induced fissions of nuclei not only ^{235}U but also other isotopes, such as ^{239}Pu, ^{238}U and ^{241}Pu, are responsible for antineutrino generation.

Calculated antineutrino spectra and beta spectra of fissile isotopes, measured in Kurchatov Institute, have shown that the number of antineutrinos per fission from ^{239}Pu is less than the number from ^{235}U.

1977

Ideas proposed by L. Mikaelyan at the conference "Neutrino-77":

- The rate of antineutrino detection gives a mean for remote power production measurements, due to direct dependence N($\bar{\nu}_e$) ~ N(fissions),
- The shape of the antineutrino spectrum can provide additional information concerning core isotopic composition

1978-1982

Several types of reactor antineutrino detectors have been developed.

1983-1994

Feasibility study was done at Rovno NPS (USSR) and later at Bugey NPS (France) in collaboration between Kurchatov In. and IN2P3.

Parallel researches of reactor antineutrinos proceeded in US, Germany and France

Reactor antineutrinos

$\mathbf{n} + {}^{238}\mathbf{U} \rightarrow {}^{239}\mathbf{U} + \gamma$

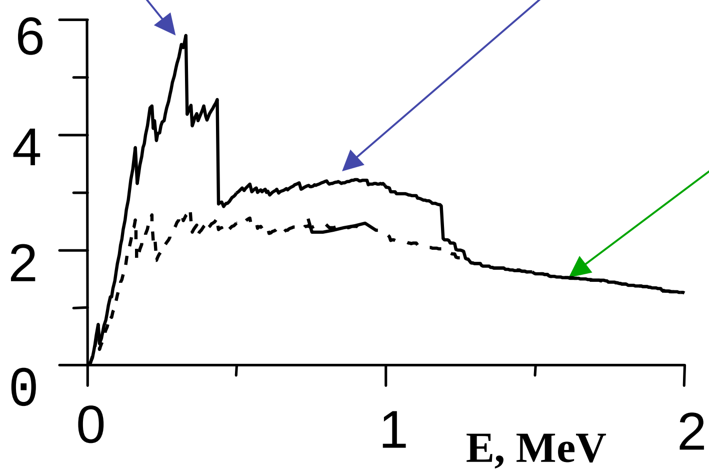
$${}^{239}\mathbf{U} \rightarrow {}^{239}\mathbf{Np} + e^{-} + \bar{\nu}_e \quad (23{,}5\ \mathrm{m})$$

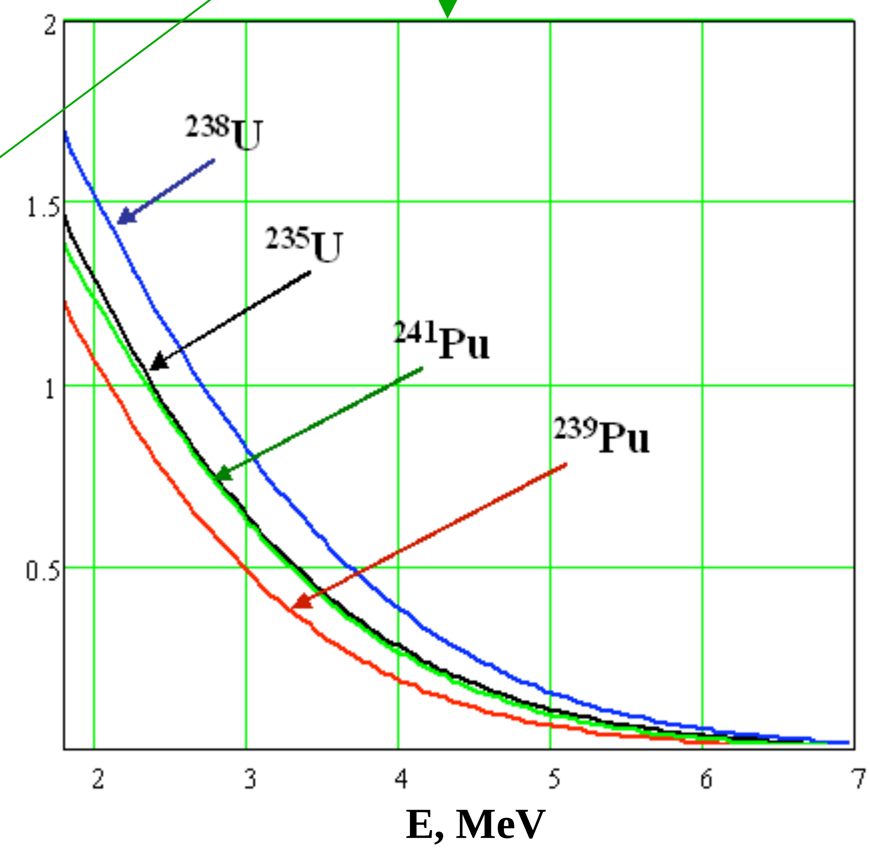
E_β= 1.26 MeV 25%
E_β= 1.19 MeV 70%
....

$${}^{239}\mathbf{Np} \rightarrow {}^{239}\mathbf{Pu} + e^{-} + \bar{\nu}_e \quad (2{,}36\ \mathrm{d})$$

E_β= 0.44 MeV 45%
E_β= 0.39 MeV 11%
E_β= 0.33 MeV 41%
....

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e}$$





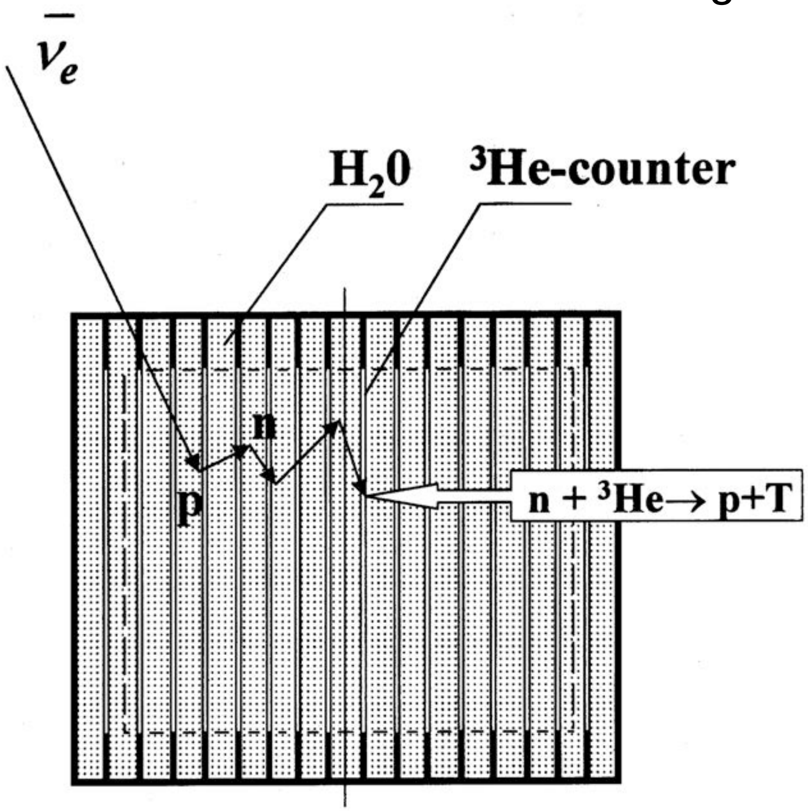
(0-1.26 MeV) namber of $\bar{\nu}_e$ per fission	
1.2 (from n captures)	2.7 (from fissions)

Antineutrino was detected
via the reaction, used for the first time by F. Reines and C.L. Cowan:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Integral type detectors was based on the detection of only neutrons from the reaction.

- The neutron signal $n + {}^3He \rightarrow p + T + 764 keV$



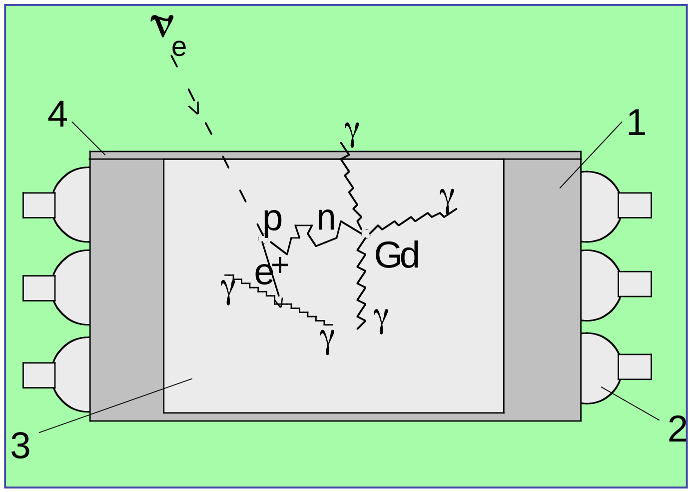
Feducial volume 750 l
256 ^{3}He-counters
Efficiency 0.4
B.-g. 2300÷2600 1/d

Lacks:
Very high cost, n b-g.

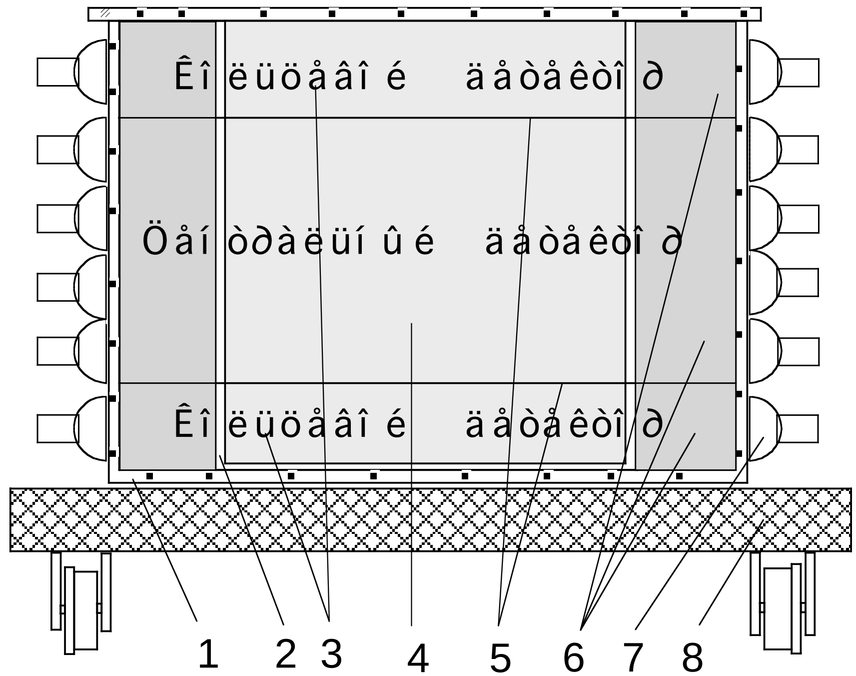
Spectrometers with liquid Gd-loaded scintillator

Antineutrino was detected by means of the delay coincidence:

- The positron signal $T = E(\bar{\nu}_e) - 1.8MeV(thresold) + m_e c^2$
- The neutron signal $n + H \,\&\, Gd \to \gamma ...(2.2\& \sim 8MeV)$



240 l, 24 PMTs
300 events per day (1.4GW)
90 b-g ev. per day
R = 18 m



Feducial volume (4) 510 l
Gamma-catcher (3) 540 l
Buffer (light guide) (6) 84 PMTs (7)
R = 18 m 1000 events per day (1.4GW)
200 b-g ev. per day

Lacks:
Stability, cost, compatibility with materials, high accid. b-g.

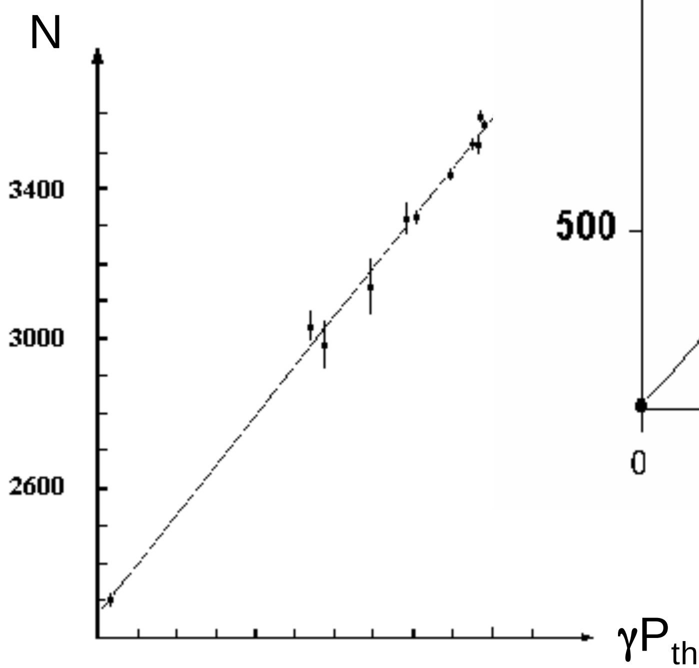
Confirmation of feasibility of antineutrino detection technology

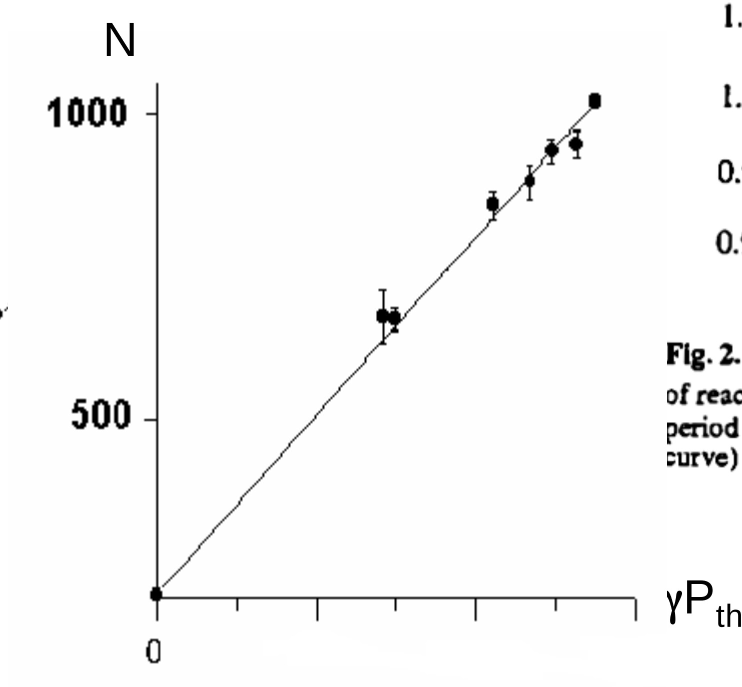
(Rovno NPS, PWR VVER-440, Pth=1.4GW)

The rate vs. reactor power

The rate of the detector

$$N = B\text{-}g + A\times\gamma\times P_{th}$$





The burn up effect

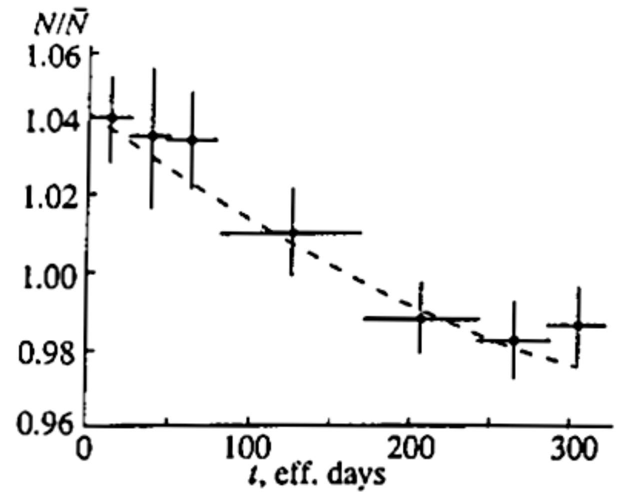


Fig. 2. Variation of the ratio of the counting rate N for events of reaction (1) to the average value $\bar{N}$ during the operating period of the reactor: (points) experimental data and (dashed curve) results computed by using the spectra from [11, 15].

A – the constant value

γ - the burn up factor, taking into account a change of the reactor core composition

Measurement of antineutrino spectrum

(Rovno NPS, PWR VVER-440, Pth=1.4GW)

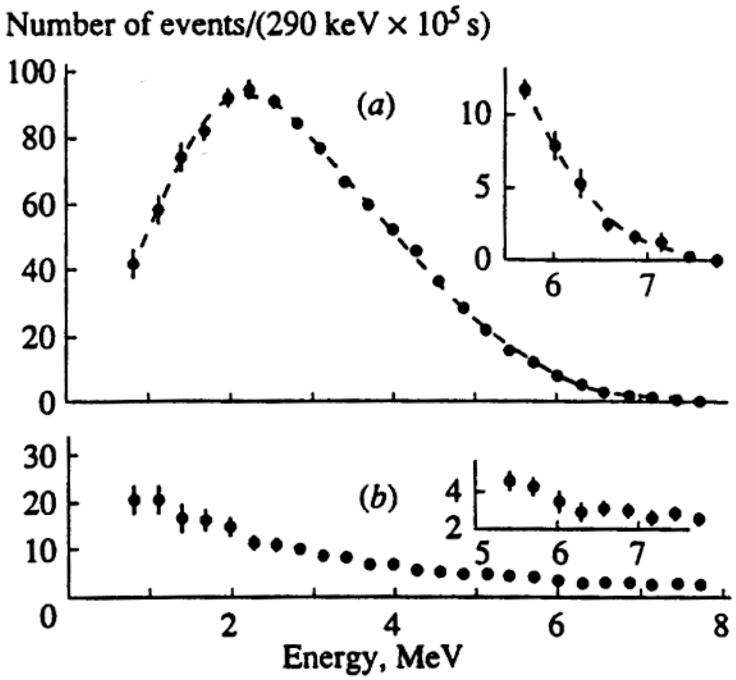


Fig. 1. Spectrum of (*a*) positrons from inverse β decay and (*b*) events of the correlated background: (points) experimental data and (dashed curve) approximation.

The burn up effect

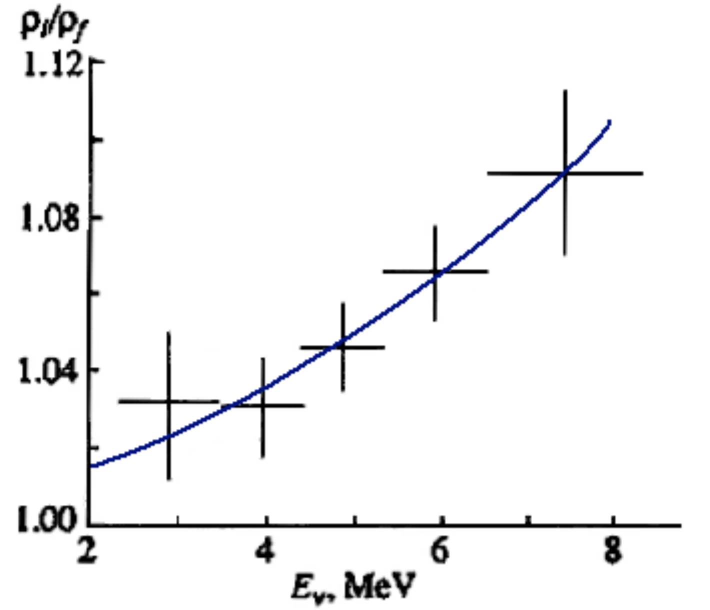
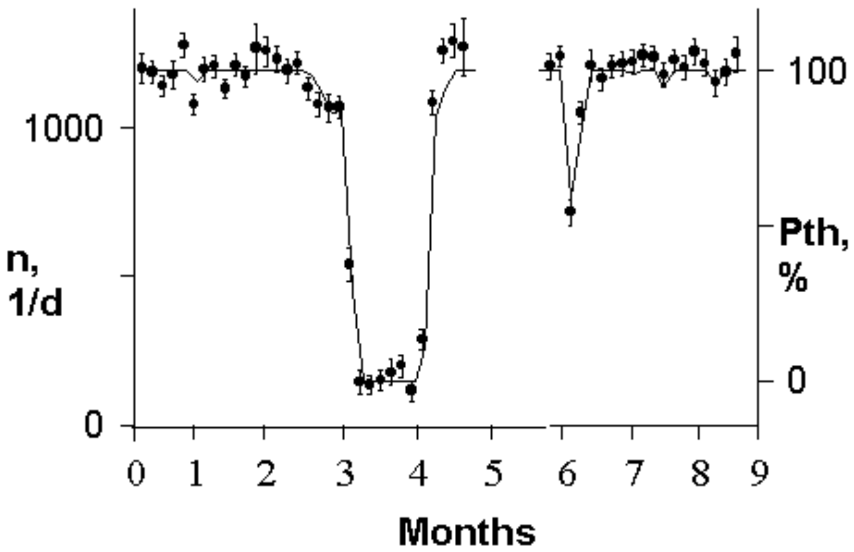


Fig. 3. Ratio ρ_i/ρ_f of the antineutrino spectra at the beginning and end of the operating period of the reactor: (points) experimental data and (dashed curve) results computed by using the spectra from [11, 15].

Examples of monitoring

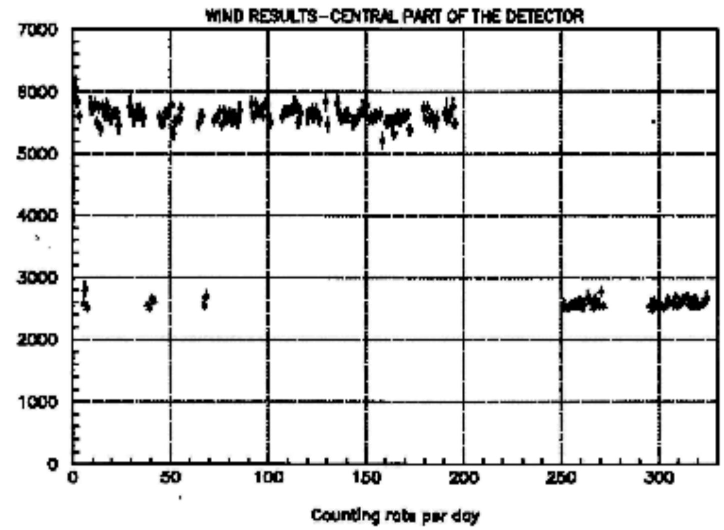
Rovno NPS

(spectrometer, PWR, Pth=1.4GW)



Bugey NPS

(integral, PWR, Pth=2.8GW)



Identification of unauthorized reactor regime, such as:

- change of a level of fuel irradiation and rate of plutonium production,

- unforeseen reactor shutting down for unloading and replacement of fuel

can be immediate detected and considered as a reason for revision.

Current status

At present R&D are conducted in collaboration:

- All-Russian Research Institute of Automatics, Moscow
- Institute for Physical Chemistry RAS, Moscow
- “Marathon” Company, Moscow
- & Kurchatov Institute, Moscow

Basic goal

To make it impossible to divert nuclear materials or modify operating modes of nuclear reactors without immediate detection

For this purpose we intent

To develop and introduce new (additional) means for existing and new nuclear reactors that will allow the IAEA to monitor and verify nuclear material

Nearest strategy

- Development of high reliability, remote and unattended monitoring detector.
- International collaboration for conducting testing and demonstration.
- Research & development of new approaches and methods.
- An exchange of information concerning best methods for security and accounting of nuclear materials.
- Incorporation of antineutrino detection technology for safeguards into the design for new nuclear energy systems.

New project for remote (10-20 m) monitoring of reactors

Up to now methods of antineutrino detection were considered in the frame of basic researches.

Manufacturing of each detector was related with development and introduction of new technologies, materials, sensitive elements etc.
Characteristics of each detector were studied and were taken under permanent control.
Engineering solutions didn’t always turn out to be successful, and this resulted to unstable operation and the need for continual maintenance of detectors.

During the Chooz experiment, the Gd-loaded scintillator filling the target showed a fast and unexpected degradation of its transparency.

It is evident that development of antineutrino detection technology and production of the tool for practical applications should meet some other requirements, such as:

- use of well-known proved technologies,
- selection of materials and detector elements with known characteristics,
- long-term stability of operation,
- easiness of servicing and data analysis,
- optimum of sensitivity for given task solution etc.

Requirements to the detector

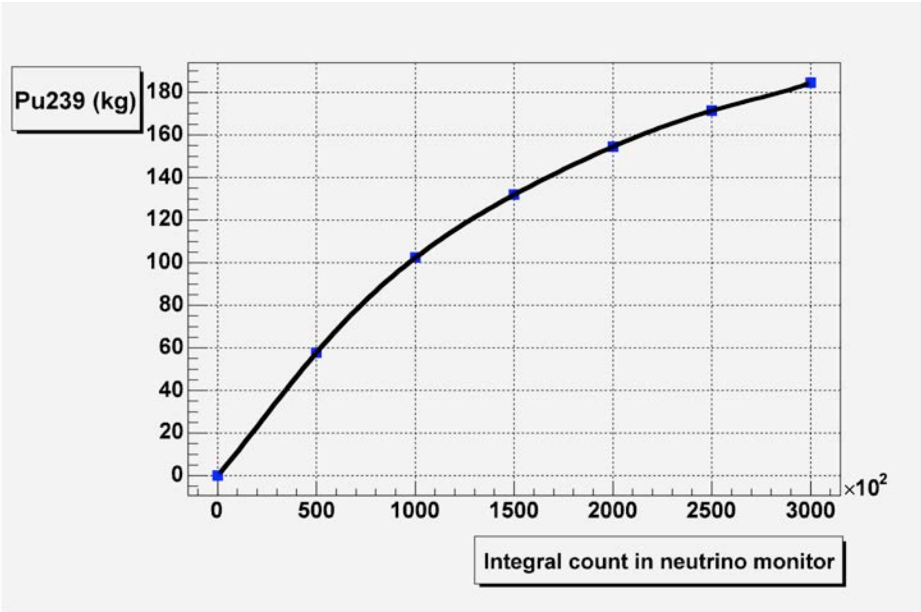
The detector is intended for:

- the monitoring of daily power production of VVER-1000 type reactor (Pth=3GW) with the accuracy of 2÷3% (68% C.L.) at the distance of 15-20 m from the core,

-the detection of shutting down of the reactor on the confidence level of 95% during 2-3 hours

- the evaluation of plutonium isotope accumulation according to the data of antineutrino flux measurement (not direct measurement)

A demonstration of the plutonium accumulation in the VVER-440 reactor (thermal power 1400 MW), based on the measured rate of antineutrino events.

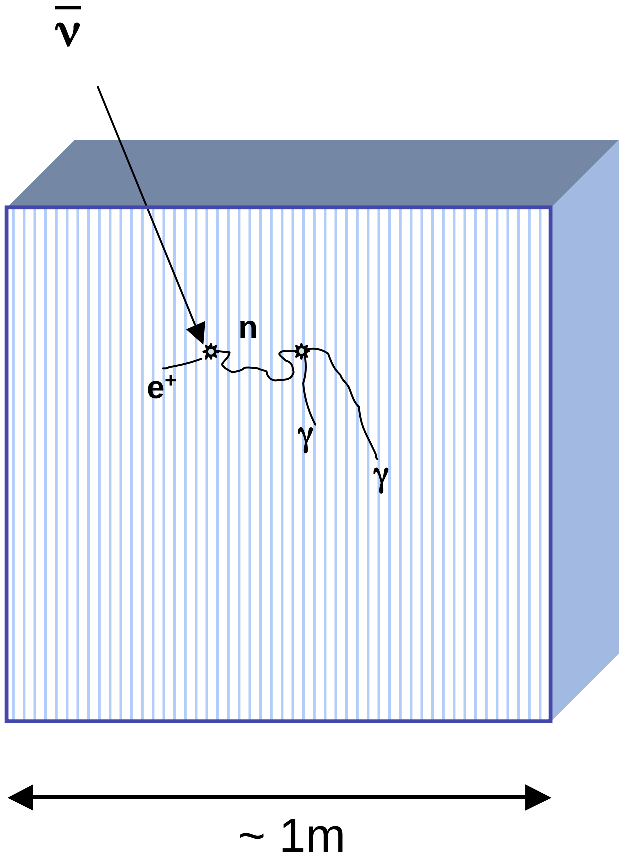


Antineutrino rate: ~1000 events/d

The standard code (БИПР-5) for the calculation of the reactor (VVER-440) parameters was used

The detector conception

The target

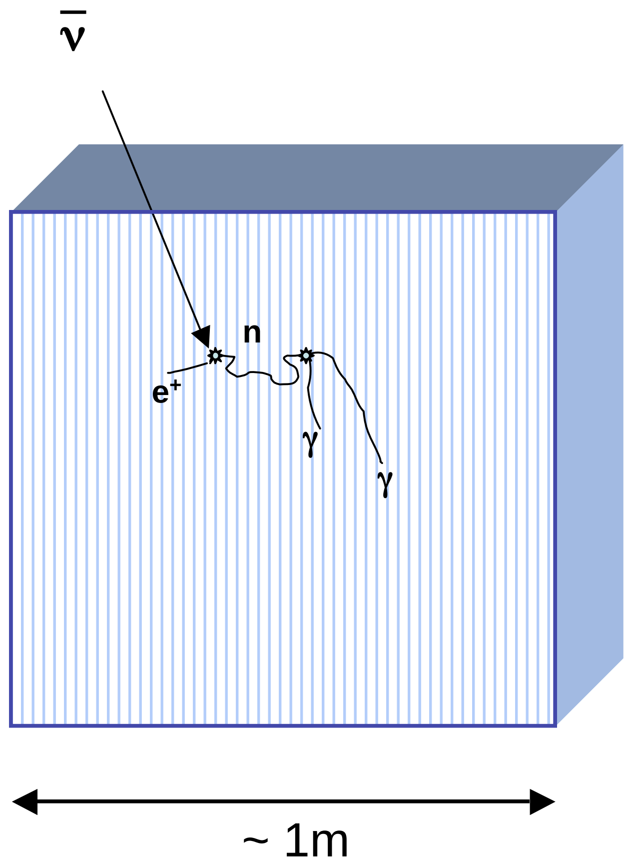


$$\bar{\nu}_e + p \rightarrow n + e^+$$

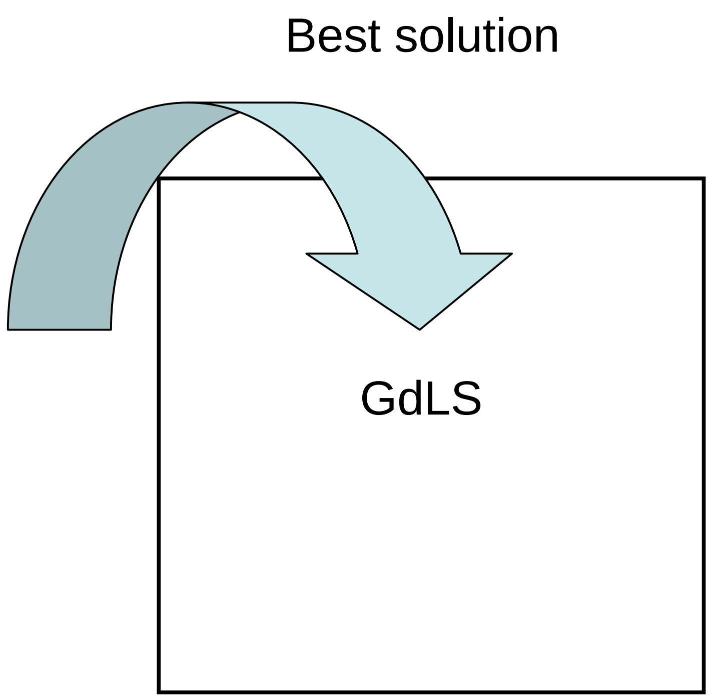
For ~ 1m^3 scale target filled with LS and the efficiency of antineutrino detection ε ~ 0.3÷0.4, counting rate is expected to be 2000÷3000 events per day at the distance of 15-20 m from reactors with the thermal power Pth=3 GW.

How to reach this efficiency keeping appropriate signal/b-g ratio?

The target



Gd loaded scintillator



Lacks:
Stability ?,
Cost,
Compatibility with materials ?

Is there a hope for success?

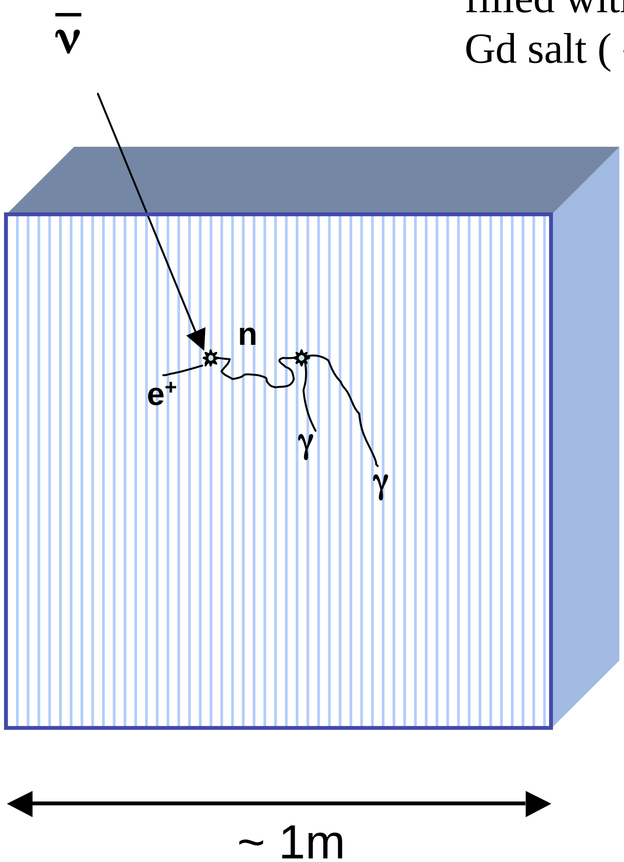
The Heidelberg, Gran Sasso and Moscow (Institute for Physical Chemistry RAS) groups of the Double Chooz collaboration have been producing Gd-loaded scintillator since 2003.

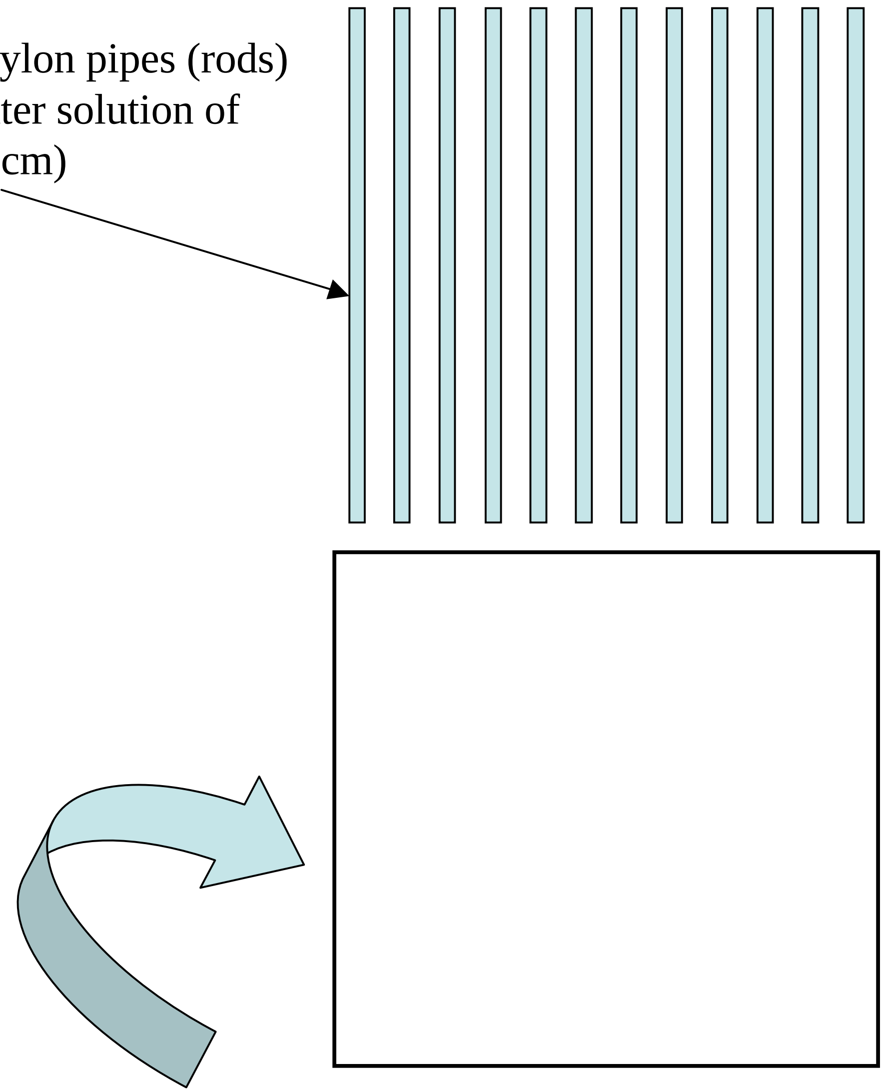
The target

Alternative solution

Rods are arranged vertically in the form of a square matrix of 18 x 18 with 54 mm step.
Gadolinium concentration is 15 g/l (for metal).

Transparent nylon pipes (rods) filled with water solution of Gd salt (~∅2cm)

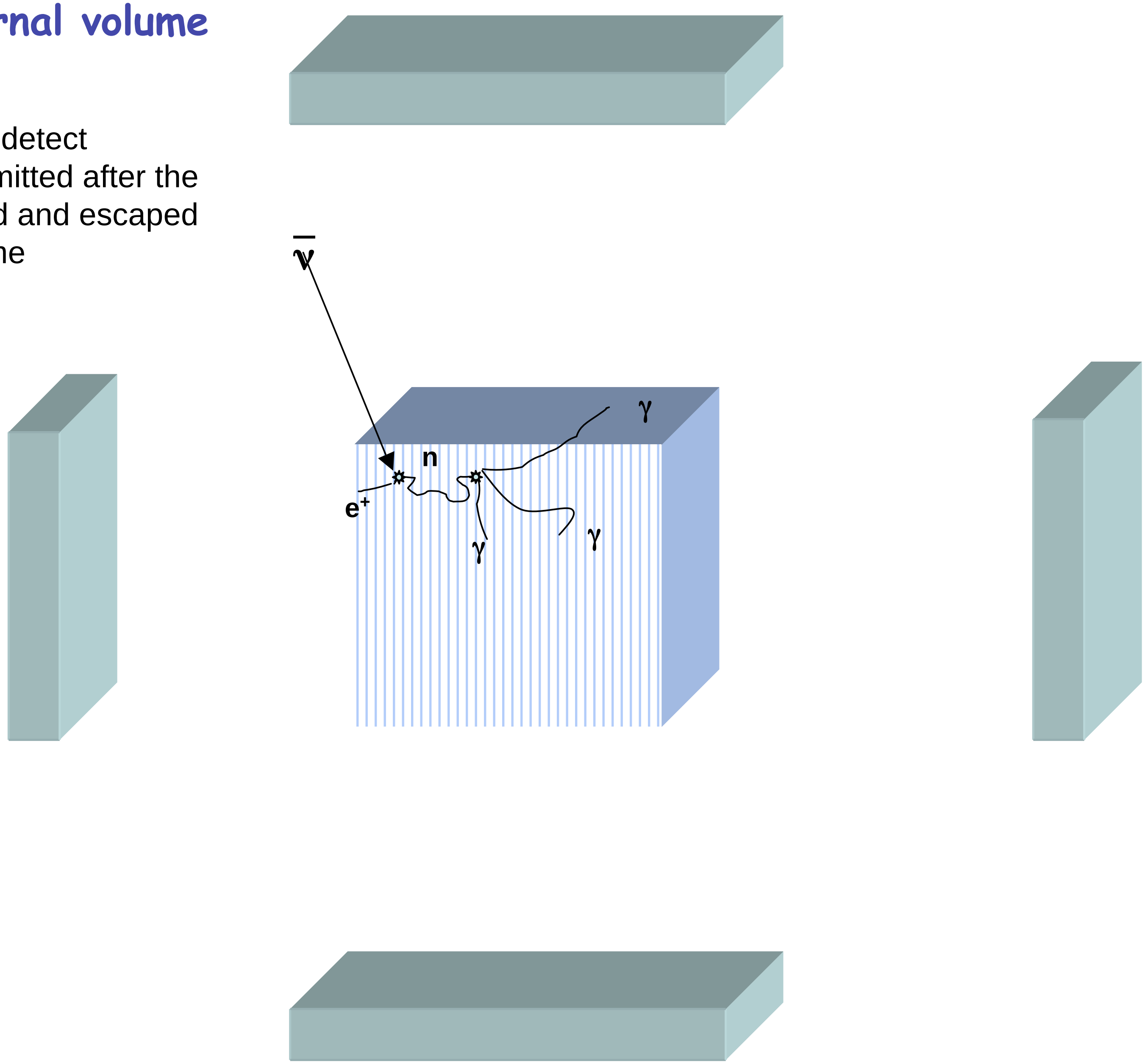




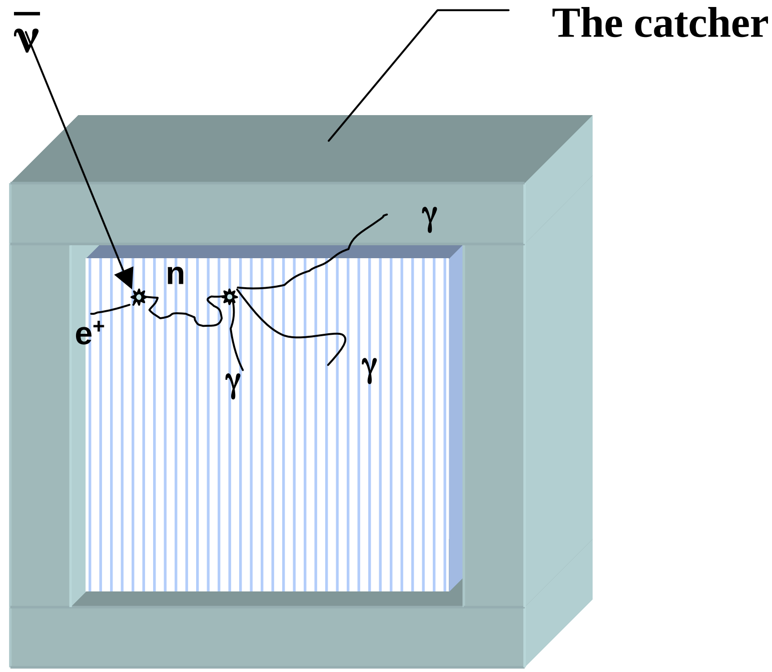
Stable Gd-free stintillator, for ex.:
PC/dodecan + PPO/Bis-MSB, LAB + PPO

The external volume

the purpose: to detect
the gamma's emitted after the
n capture on Gd and escaped
the target volume



The target + the external volume

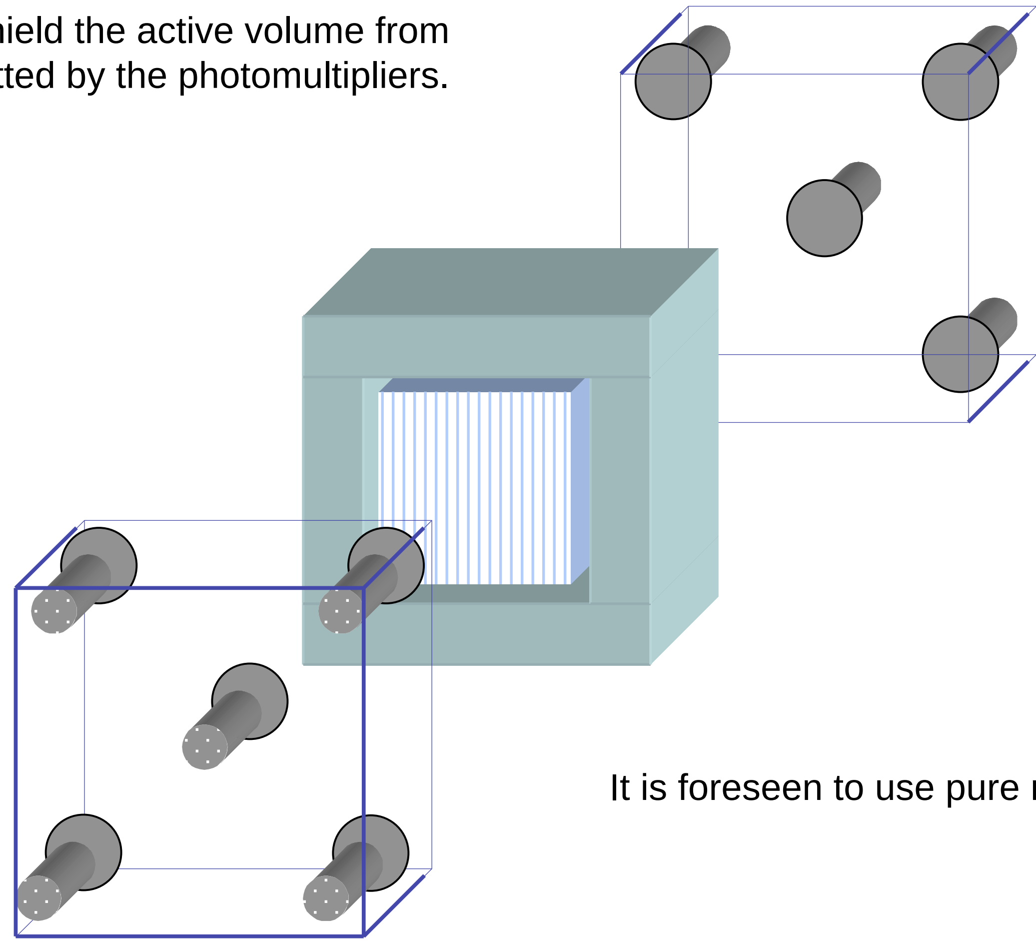


The external volume of 300 mm thickness is filled with the Gd-free scintillator.

The external volume plays the role of
- the gamma catcher (for the neutron event) to improve the detection of Gd gamma-rays escaping from the target,
- the veto system (for the positron event) to suppress background caused by cosmic radiation.

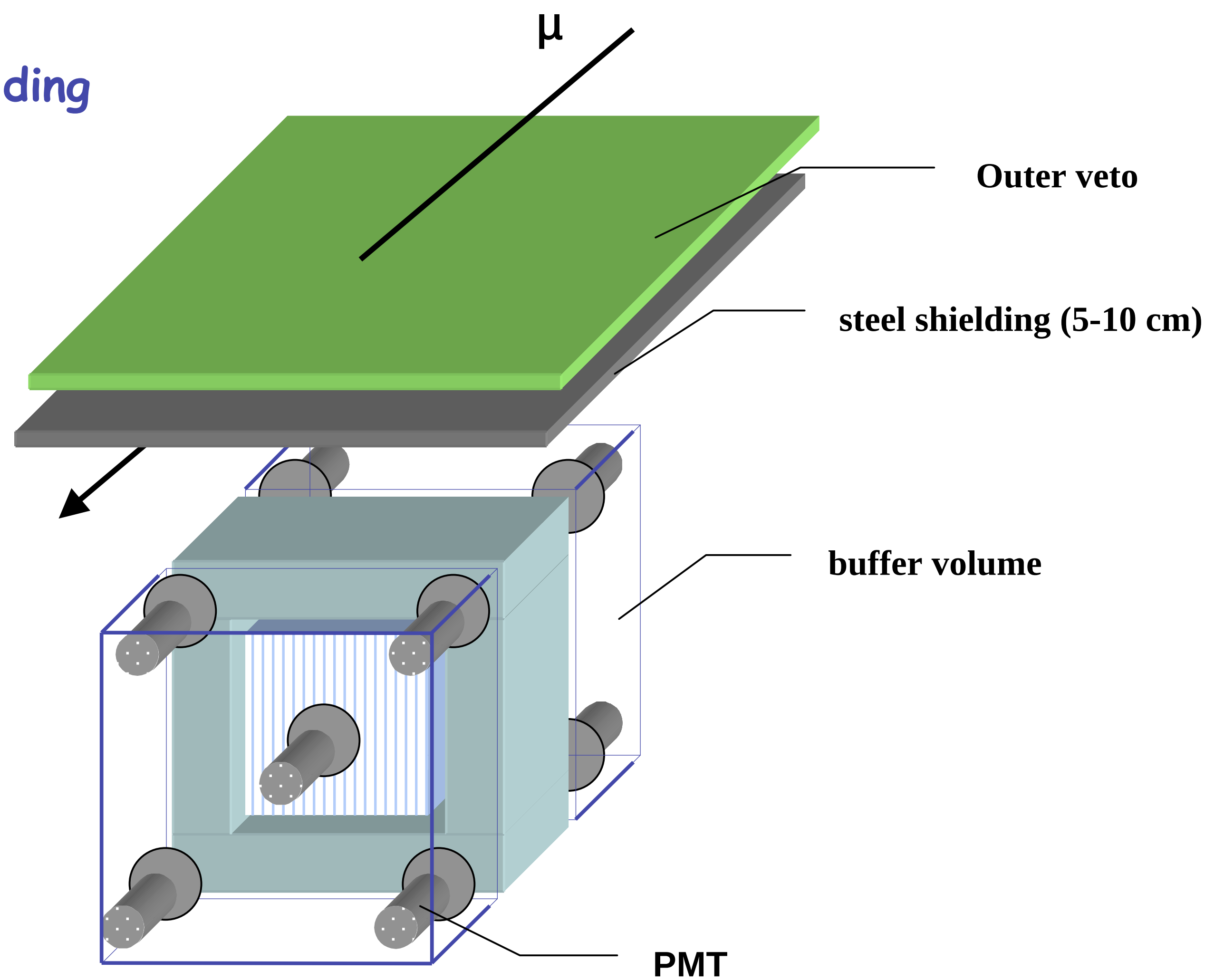
Buffers with PMTs

Buffers should shield the active volume from gamma rays emitted by the photomultipliers.



It is foreseen to use pure mineral oil in these regions

The detector+shielding

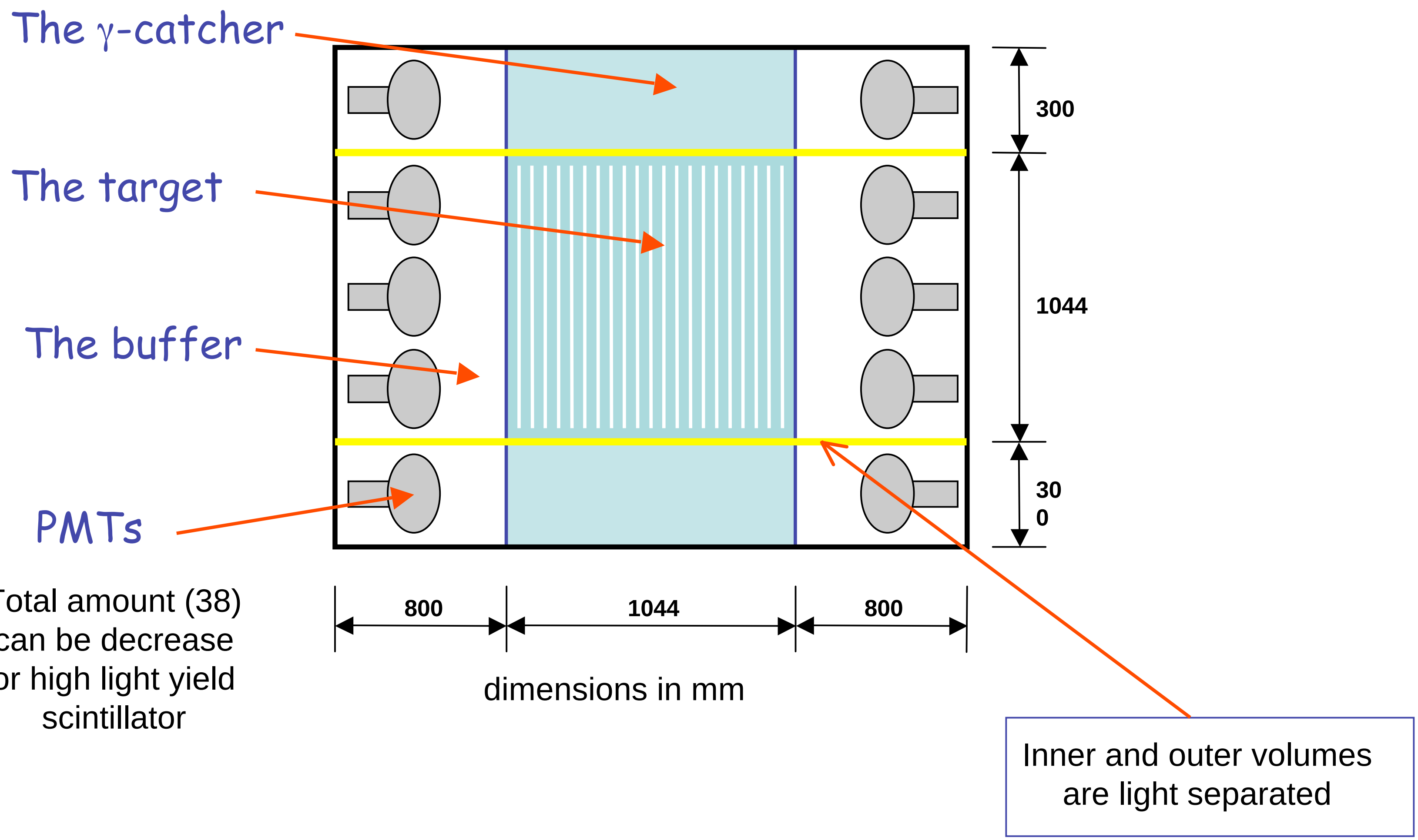


The scheme of the detector

Schemes are the same for both version of the detector:

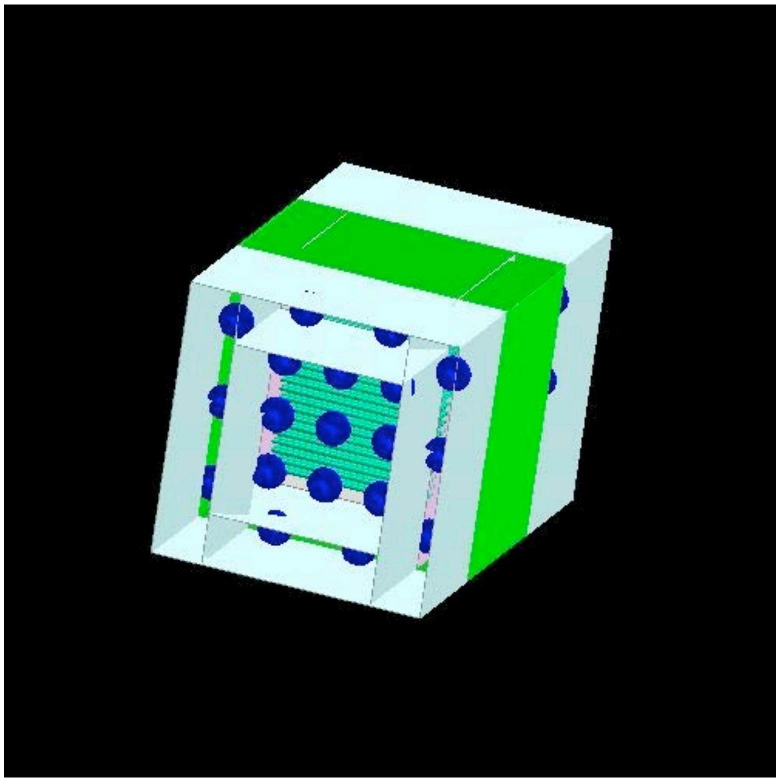
- Gd loaded scintillator

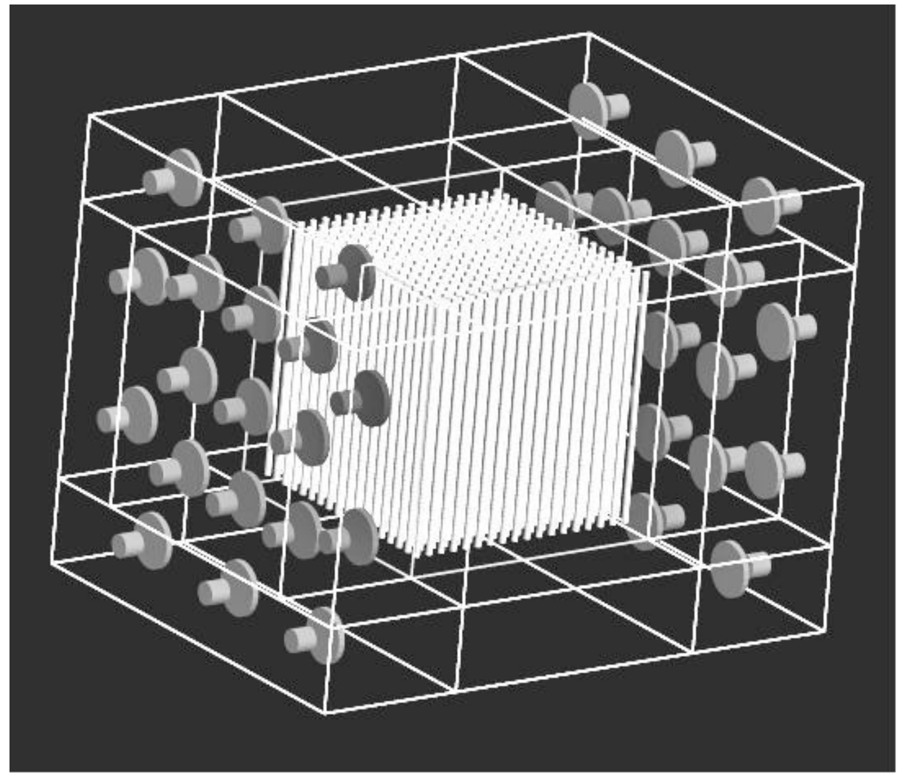
- Scintillator + Gd loaded rods



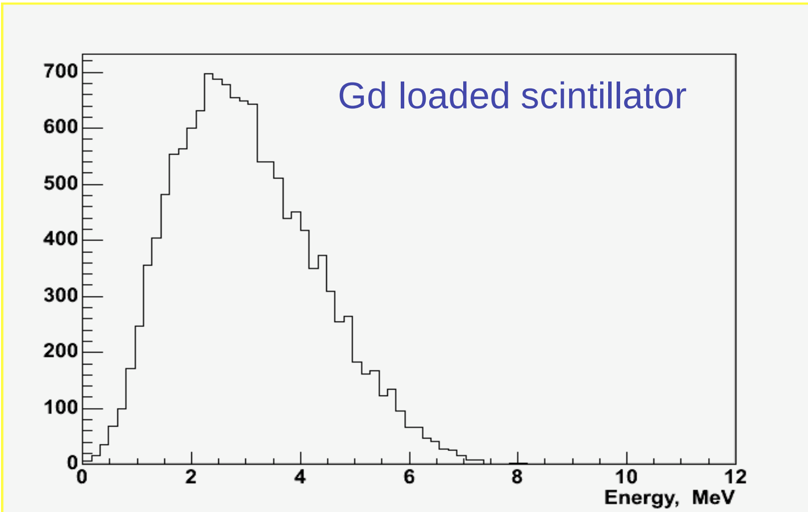
Total amount (38) can be decrease for high light yield scintillator

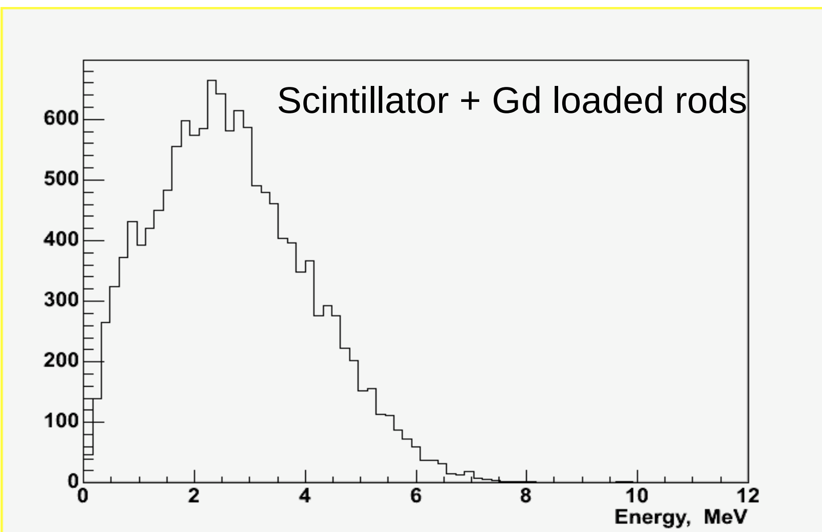
GEANT4 simulation of the detector



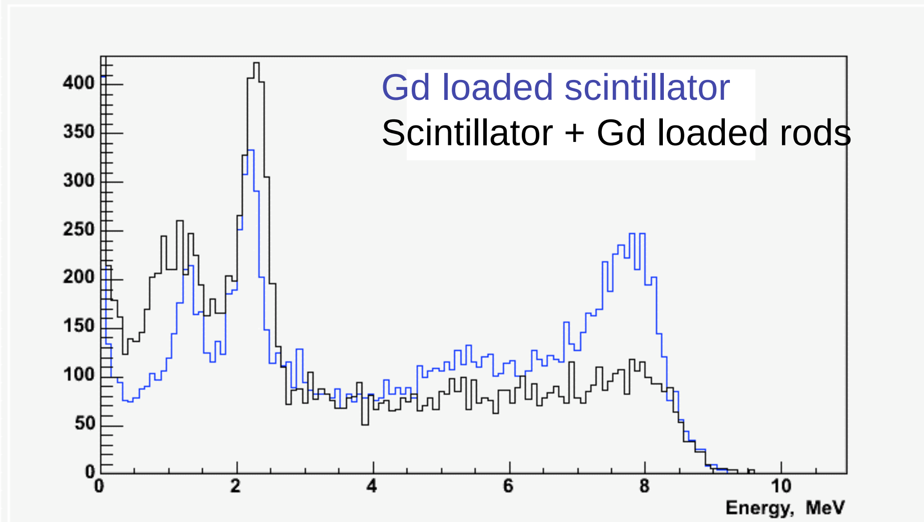


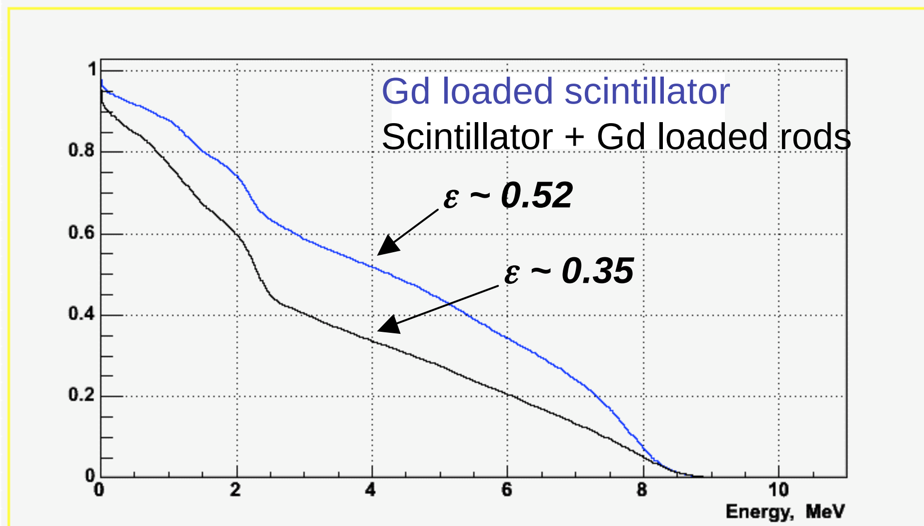
the positron event





the neutron event





Expected background

1. The detector should be installed at the depth of about 20 m.w.e. to suppress the nuclear component of cosmic radiation.

2. The accidental background $N_{accid} = n_1 \times n_2 \times (T \sim 100\ \mu s) = 40 \div 300$ events/day

Main contributions to gamma background (from ~1 MeV) will be made by PMTs and materials surrounded
the detector.
The total activity was evaluated to be $(5 \div 35)\ s^{-1}$ for selected thickness of passive iron shield (5-10 cm).
The rate from 3-4 MeV is expected to be $\sim 1\ s^{-1}$ (from data of RONS detector at Rovno NPS)

N_{accid} can be accurately measured during data taking.

3. The correlated background.

Main sources of the correlated background in detector will be:
a) products of the muon induced spallation within the detector;
b) fast neutrons, generated by muons outside the detector, and then come into the detector.
Results of simulations (20 m.w.e.):
a) 12 events/day per ton of the target,
b) 200-300 events/day per ton of the target.

This component of the correlated background can be suppressed by using PSD technique.

Under the efficiency of proton and positron signal separation of about 90% the expected value of correlated background in detector is equal to 30-50 event/day.

Progress in scintillator development

(Institute for Physical Chemistry RAS, Moscow)

Well known mixture: 20% PC + 80% dodecane + 2 g/l PPO (BPO) + 15 mg/l Bis-MSB

LY – 50% with respect to pure PC (~10^4 photons/MeV)
FP – 50^{o}C
Transparency > 10 m
Material compatibility, stability - OK

New development: LAB + 4 g/l PPO LAB – Linear AlkilBenzene $\mathbf{C_6H_5R}$ (R~$C_{11}H_{23}$)

LY – 98% with respect to pure PC (~10^4 photons/MeV)
FP – 147^{o}C
Transparency > 20 m
Low cost
Material compatibility, stability – study in progress

New development: LAB + 4 g/l PPO+ 1g/lGd

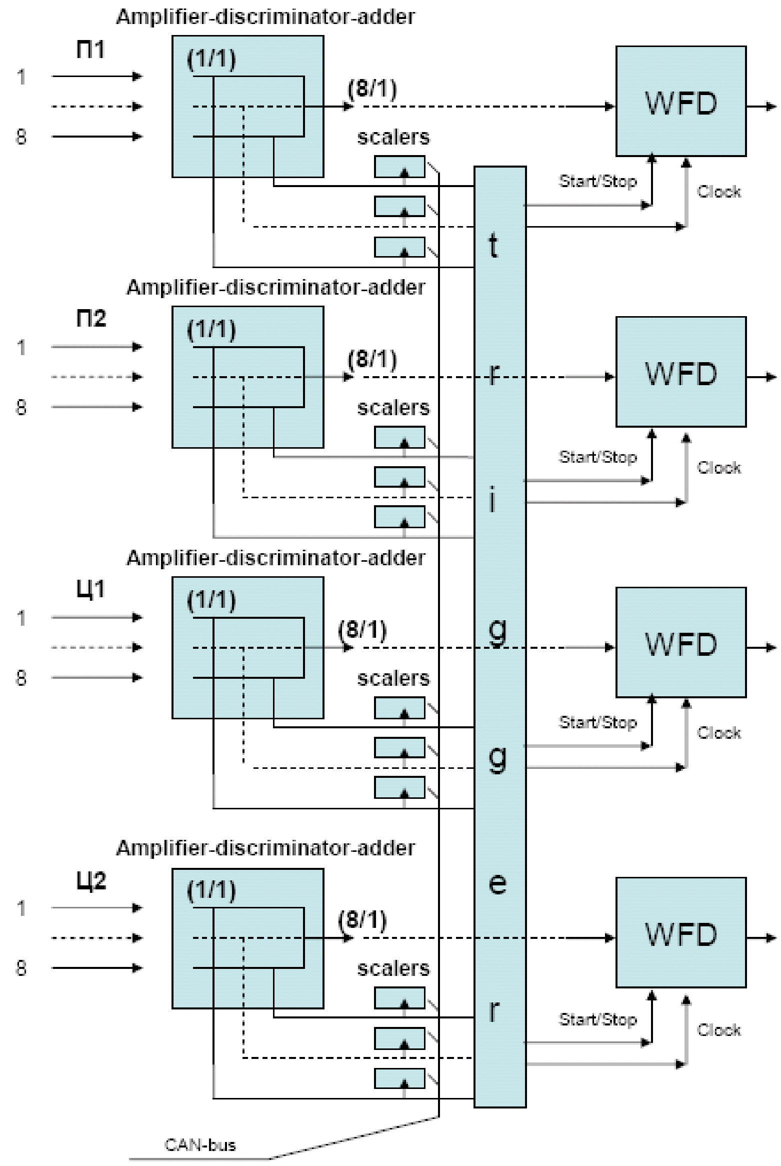
LY – 90% with respect to pure PC (~10^4 photons/MeV)
FP – 147^{o}C
Transparency > 15 m
Material compatibility, stability – study in progress

Electronics overview
(“Marathon” Company, Moscow)

Electronics:
processing signals from the detector;
distributing them to acquisition systems;
forming triggers;
monitoring parameters of the detector.

Management of reactor monitoring:
data taking;
digitizing and storing;
preliminary analysis;
calibration;
data transmission.

A mix of commercial and custom electronics:
many suitable custom made modules have been
developed for Borexino (same PMTs)



calibration

n source at the center