ORGANIC SCINTILLATORS

Igor Nemchenok
1. Scintillation method of the radiation and particles detection.
2. Organic scintillators.
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   2.2. The nature of the molecular excited states.
   2.3. Advantages.
3. Organic scintillators in the JINR Laboratory of Nuclear Problems.
      3.1.1. Polystyrene-based plastic scintillators.
      3.1.2. Linear alkylbenzene-based liquid scintillators.
   3.2. Element-loaded scintillators.
      3.2.1. B-loaded polystyrene-based plastic scintillators.
      3.2.2. Rare-earth elements-loaded polymethylmethacrylate-based plastic scintillators.
      3.2.3. Gd-loaded liquid scintillators.
      3.2.4. Gd-loaded liquid scintillator for DAYA BAY neutrino experiment.
1. Scintillation method of the radiation and particles detection

Definitions

Scintillation – short-time event of the radioluminescence with the duration no more than few microseconds.

Scintillating compound – compound which produces scintillations under the radiation.

Scintillator – the definite amount of the scintillating compound contained in the scintillation detector as an element sensitive to radiation.

Stages of the radiation detection process by the help of the scintillation detector:

- conversion of the radiation energy to the light energy by means of the luminescence;
- light photons collection to the PMT’s photocathode;
- light photons adsorption by the photocathode and photoelectrons emission;
- electrons multiplying in the PMT;
- electronics and software processing of the current ‘s impulses arising at the PMT’s outlet.
1. Scintillation method of the radiation and particles detection

Mechanism of the radioluminescence event:

• Energy transfer from radiation (or particle) to excitation and ionization of atoms and molecules and formation of secondary particles;
• Energy transfer from excited and ionized particles directly to emitting centers (atoms, molecules etc.);
• Light emission by emitting centers.

Definition

Relative light output – ratio of amplitude of pulses of scintillation detector to the same parameter of standard detector in the same experimental conditions.
1. Scintillation method of the radiation and particles detection

**Scintillation materials**

- **Inorganic**
  - Monocryotlline and polycrystalline
    - Alkali halides: NaI(Tl), CsI(Tl), CsI, CsI(Na), CsI(CO₃), LiF(W), LiF(Eu)
  - Liquefied noble gases: Ar, Kr, Xe

- **Organic**
  - Single crystals
  - Plastic
  - Liquid

**Main differences**

- **Inorganic scintillators**
  - High light output
  - “Slow”

- **Organic scintillators**
  - Low light output
  - “Fast”
2. Organic scintillators
2.1. Brief characteristic

Organic single crystals

Liquid scintillators (LS) – solutions of organic luminescent compounds and some special additives in organic liquid solvents

Plastic scintillators (PS) – solutions of organic luminescent compounds and some special additives in organic polymeric solvents
## 2. Organic scintillators
### 2.1. Brief characteristic

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Polystyrene</th>
<th>Polyvinyltoluene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm$^3$</td>
<td>1.065</td>
<td>1.03</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.58</td>
<td>1.58</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Light output, relatively to anthracene single crystal, %</td>
<td>39 – 57 (55 – 57) *</td>
<td>11 – 68 (60 – 68)*</td>
</tr>
<tr>
<td>H:C relation</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>Response function, ns</td>
<td>0.7 – 285 (2 – 3) *</td>
<td>0.7 – 285 (2 – 3)*</td>
</tr>
</tbody>
</table>

* For most wide spread scintillators
2. Organic scintillators
2.1. Brief characteristic

Definitions

**Basic (main) scintillator’s compound**:
1. transparent for scintillation photons; 2. its content predominates in scintillator.

\[ h\nu_1 \]

**Primary additive** – admixture to the basic scintillator’s compound which is able to emit optical photons under excitation received of the basic scintillator’s compound molecules.

\[ h\nu_2 (\nu_2 < \nu_1) \]

**Waveshifter (secondary additive)** – compound, incorporating to organic scintillator and converting primary additive emission to the emission with the longer wavelength.

\[ h\nu_3 (\nu_3 < \nu_2) \]
2. Organic scintillators
2.1. Brief characteristic

Demands to scintillation additives

- Intensive adsorption;
- High quantum yield;
- Overlapping of the emission spectrum of the base compound with the adsorption spectrum of the primary additive;
- Overlapping of the emission spectrum of the primary additive with the adsorption spectrum of the waveshifter;
- Emission spectrum of the waveshifter must be in the region of high spectral sensitivity of widespread PMTs or other devices.

Emission spectrum of the polystyrene-based PS (primary additive – p-terphenyl; waveshifter – POPOP) and typical curve of the PMT’s spectral sensitivity (entrance window - borosilicate glass, bialkaline photocathode.)
2. Organic scintillators
2.1. Brief characteristic

**Primary additives**
- p-terphenyl (PPP)
- 2,5-diphenyloxazole (PPO)
- 2-(4-biphenylyl)-5-phenyloxazole (BPO)
- 2-phenyl-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD)
- 2-(1-napthyl)-5-phenyloxazole (α-NPO)

**Waveshifters**
- 1,4-di-(5-phenyl-2-oxazolyl)benzene (POPOP)
- 1,4-di-(4-methyl-5-phenyl-2-oxazolyl)benzene (dimethyl-POPOP)
- 1,4-bis-(2-methylstyryl)benzene (bis-MSB)
2. Organic scintillators
2.1. Brief characteristic

Aromatic compounds (arenes) – large group of the compounds of the carbocyclic series with molecules containing stable cyclic atomic bunching of six carbon atoms (benzene ring) possessing special chemical characteristics.

Hukkel rule: compounds which molecules form plane cycle and contain $4n + 2$ (where $n$ — nonnegative integer) $\pi$-electrons are aromatic.
2. Organic scintillators
2.1. Brief characteristic

Kerosene (light fraction – white spirit)

Nonane – $C_9H_{20}$

Hexadecane – $C_{16}H_{34}$

Polymethylmethacrylate

Secondary solvent – naphthalene
2. Organic scintillators

2.2. The nature of the molecular excited states

The main photophysical processes

<table>
<thead>
<tr>
<th>Photophysical process</th>
<th>Duration, seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adsorption</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Fluorescence (singlet-singlet light emission)</td>
<td>$10^{-9} - 10^{-7}$</td>
</tr>
<tr>
<td>Phosphorescence (triplet-singlet light emission)</td>
<td>$10^{-4} - 10^{-2}$</td>
</tr>
<tr>
<td>Internal conversion (nonradiative transition to lower state of the same multiplicity)</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>Intercombination conversion (nonradiative transition from excited singlet state to excited triplet state)</td>
<td>$10^{-2} - 10$</td>
</tr>
<tr>
<td>Vibrational-rotational relaxation</td>
<td>$10^{-14} - 10^{-12}$</td>
</tr>
</tbody>
</table>

The diagram of electronic-vibrational states of polyatomic molecule and paths of radiative (solid arrows) and nonradiative (dashed arrows) transitions.
2. Organic scintillators
2.3. Advantages

• Fast response;

• High stability to different actions (radiation resistance, photo resistance, thermo resistance, moisture resistance, ...);

• Relative simplicity of construction of detectors of any shape and configuration;

• Possibility of large-scale detectors construction;

• Relatively low cost;

• Possibility of using simple methods of decreasing of radioactive impurity concentrations;

• Possibility of directional changing of properties due to molecular nature of luminescence.
2. Organic scintillators
2.3. Advantages

<table>
<thead>
<tr>
<th>Elements or isotopes</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$Li, $^{10}$B, $^{113}$Cd, $^{155}$Gd, $^{157}$Gd, $^{235}$U</td>
<td>Neutron detectors, searching for neutrinos oscillations</td>
</tr>
<tr>
<td>$^{176}$Yb, $^{160}$Gd, $^{115}$In, $^{100}$Mo, $^{37}$Cl</td>
<td>Detection of Sun neutrinos</td>
</tr>
<tr>
<td>Pb</td>
<td>Detection of astrophysics neutrinos</td>
</tr>
<tr>
<td>$^{19}$F, $^{73}$Ge</td>
<td>Searching for “Dark Matter”</td>
</tr>
<tr>
<td>$^{150}$Nd, $^{160}$Gd, $^{100}$Mo, $^{130}$Te, $^{82}$Se</td>
<td>Searching for double $\beta$-decay</td>
</tr>
<tr>
<td>Pb, Sn, W, Hg, Bi</td>
<td>High energy physics</td>
</tr>
</tbody>
</table>
3. Organic scintillators in the JINR Laboratory of Nuclear Problems

- Scintillators
  - Unloaded (C, H – based)
    - Plastic (polystyrene)
    - Liquid (LAB)
  - Element-loaded
    - B-loaded
    - Gd-loaded
    - Rare-earth loaded
      - Nd-loaded
        - Plastic
          - PMMA
        - LAB
          - PMMA
        - Polystyrene
          - α-Methylnaphtalene
          - Phenylcyclohexane
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.1. Scintillators of usual composition (C, H – based)
3.1.1. Polystyrene-based PSs

Basic compound: polystyrene

Primary additive: 1,4-diphenylbenzene (p-terphenyl)

Waveshifter: 1,4-di-(5-phenyl-2-oxazolyl)benzene (POPOP)
### 3. Organic scintillators in the JINR Laboratory of Nuclear Problems

#### 3.1. Scintillators of usual composition (C, H – based)

#### 3.1.1. Polystyrene-based PSs

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic compound</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>Fire safety</td>
<td>Yes</td>
</tr>
<tr>
<td>Toxicity</td>
<td>No</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>No</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>1.05</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.58</td>
</tr>
<tr>
<td>Light output, relatively to anthracene single crystal, %</td>
<td>52</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$ of luminescence, nm</td>
<td>421</td>
</tr>
<tr>
<td>Transparency, cm</td>
<td>170</td>
</tr>
<tr>
<td>Response function, ns</td>
<td>2.5</td>
</tr>
<tr>
<td>Number of hydrogen atoms, cm⁻³, $\times 10^{22}$</td>
<td>4.85</td>
</tr>
<tr>
<td>Number of carbon atoms, cm⁻³, $\times 10^{22}$</td>
<td>4.85</td>
</tr>
</tbody>
</table>
Methods of plastic scintillators production:
- Radical bulk polymerization;
- Suspension polymerization;
- Methods of plastics processing: pressure molding, extrusion.

Advantages of radical bulk polymerization:
- Best counting and spectrometric properties;
- High transparency;
- Possibility of production of large size and different shape scintillators.

Main stages of PS production by radical bulk polymerization:
- Dehydration of raw styrene;
- Styrene rectification under the reduced pressure;
- Luminescent additives dissolution in styrene;
- Filtration and loading styrene solution to the polymerization mold;
- Polymerization:
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.1. Scintillators of usual composition (C, H – based)
3.1.1. Polystyrene-based PSs

Temperature conditions of the polymerization stage
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.1. Scintillators of usual composition (C, H – based)
3.1.1. Polystyrene-based PSs
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3.1. Scintillators of usual composition (C, H – based)
3.1.1. Polystyrene-based PSs
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.1. Scintillators of usual composition (C, H – based)
3.1.2. Linear alkybenzene-based LS

Requirements to LS for large-scale detectors:

- High scintillation efficiency;
- High transparency;
- High flash point;
- High stability;
- Low toxicity;
- Low solvent action to acrylic plastics;
- Availability.
LAB is the large-capacity product of the petrochemical industry. The main LAB application is the production of the biodegradable synthetic detergents. LAB is a mixture of the monoalkyl benzene derivatives with the number of the carbon atoms in the side chain from 9 to 14. The main LAB components contain from 10 to 13 carbon atoms in the side chain. There are about 80% ÷ 85% of the 1-phenylalkanes

\[
\text{C}_n\text{H}_{2n-1}\text{CH}_2, \text{ where } n = 8 \div 13
\]

and about 15% ÷ 20% of the 2-phenylalkanes

\[
\text{C}_n\text{H}_{2n-1}\text{CH}, \text{ where } n = 7 \div 12
\]

in the LAB.
### 3. Organic scintillators in the JINR Laboratory of Nuclear Problems

#### 3.1. Scintillators of usual composition (C, H – based)

#### 3.1.2. Linear alkybenzene-based LS

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity, g/cm³</td>
<td>0.8580 – 0.862</td>
</tr>
<tr>
<td>Boiling point, °C</td>
<td>280 – 311</td>
</tr>
<tr>
<td>Flash point, °C</td>
<td>147</td>
</tr>
<tr>
<td>Mean value of the molecular mass, g/Mole</td>
<td>238 – 245</td>
</tr>
<tr>
<td>No of H atoms per 1 cm³</td>
<td>6.29 × 10²²</td>
</tr>
</tbody>
</table>
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.1. Scintillators of usual composition (C, H – based)
3.1.2. Linear alkybenzene-based LS

<table>
<thead>
<tr>
<th>Primary additive</th>
<th>Waveshifter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,5-diphenyloxazole (PPO)</td>
<td>1,4-bis-(5-phenyl-2-oxazolyl)benzene (POPOP)</td>
</tr>
<tr>
<td>2,5-diphenyloxazole (PPO)</td>
<td>1,4-bis(4-methyl-5-phenyl-2-oxazolyl)benzene (dimethyl-POPOP)</td>
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</tbody>
</table>
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.1. Scintillators of usual composition (C, H – based)
3.1.2. Linear alkybenzene-based LS

Source – $^{137}$Cs

Standard sample:
solvent – pseudocumene;
primary additive – PPO (5 g/L);
waveshifter – bis-MSB (10 mg/L).
3. Organic scintillators in the JINR Laboratory of Nuclear Problems

3.1. Scintillators of usual composition (C, H – based)

3.1.2. Linear alkybenzene-based LS

![Intensity vs. Wavelength Graph](image)

- **0.5% PPO**
- **0.5% PPO + 0.0025% POPOP**
- **LAB**

**Exitation - 275 nm**
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.1. Scintillators of usual composition (C, H – based)
3.1.2. Linear alkybenzene-based LS

Source – $^{207}$Bi
$\bar{\epsilon}_K$: 482 keV and 976 keV
$\gamma$: 569.7 keV and 1064 keV

20 ml teflon
5 mm Al filter
Al-mylar film
3. Organic scintillators in the JINR Laboratory of Nuclear Problems

3.1. Scintillators of usual composition (C, H – based)

3.1.2. Linear alkybenzene-based LS

\[ V = 20 \text{ ml} \]
\[ H = 1.17 \text{ cm} \]
### 3. Organic scintillators in the JINR Laboratory of Nuclear Problems

#### 3.1. Scintillators of usual composition (C, H – based)

#### 3.1.2. Linear alkybenzene-based LS

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Light output*</th>
<th>FWHM, %</th>
<th>Transparency (430 nm), m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5% PPO, 0.0025% POPOP</td>
<td>1.02</td>
<td>7.95</td>
<td>9.8</td>
</tr>
<tr>
<td>0.5% PPO, 0.0025% dimethyl-POPOP</td>
<td>1.00</td>
<td>7.96</td>
<td>3.0</td>
</tr>
<tr>
<td>0.5% PPO, 0.0025% bis-MSB</td>
<td>1.02</td>
<td>7.92</td>
<td>9.8</td>
</tr>
</tbody>
</table>

*Relatively to the standard sample:

- liquid solvent – pseudocumene;
- primary additive – PPO (5 g/L);
- Waveshifter – bis-MSB (10 mg/L)
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators

Requirements to element-containing additives:

• Good solubility in organic media;
• Optical transparency (300 - 600 nm);
• Thermal stability;
• Stability to atmospheric $O_2$;
• Stability to hydrolysis;
• Photostability;
• Stability to other actions.
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.1. B-loaded polystyrene-based PS

Experimental samples:
diameter — 3 cm, height — 0.9 cm.
Mass fraction of B:
0.38%, 0.75%, 2% and 5%

Polymeric base: polystyrene

-o-Carborane ($C_{10}B_{12}H_{12}$)

Activator: 1,4-diphenylbenzene (p-terphenyl)

Waveshifter: 1,4-di-(5-phenyl-2-oxazolyl)benzene (POPOP)
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.1. B-loaded polystyrene-based PS

Diameter — 7 cm,

Height — 5.7 cm
### 3. Organic scintillators in the JINR Laboratory of Nuclear Problems

#### 3.2. Element-loaded scintillators

#### 3.2.1. B-loaded polystyrene-based PS

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Mass fraction of B, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>1.05</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.57</td>
</tr>
<tr>
<td>Number of B atoms per cm³, ×10²²</td>
<td>0</td>
</tr>
<tr>
<td>Number of H atoms per cm³, ×10²²</td>
<td>4.85</td>
</tr>
<tr>
<td>Number of C atoms per cm³, ×10²²</td>
<td>4.85</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$ of luminescence, nm</td>
<td>421</td>
</tr>
<tr>
<td>Transparency* ($\lambda_{\text{max}}$), %</td>
<td>86.8</td>
</tr>
<tr>
<td>Relative light output, %</td>
<td>100</td>
</tr>
<tr>
<td>Thermal neutrons (E ≤ 0.5 eV) detection efficiency, %</td>
<td>0</td>
</tr>
</tbody>
</table>

*Relatively to air
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.2. Rare-earth elements-loaded PMMA-based PSs
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.2. Rare-earth elements-loaded PMMA-based PSs

Rare earth containing additive

$$\text{LnX}_3 \times 6\text{H}_2\text{O}$$
Salt ($X = \text{Cl}^-, \text{NO}_3^-$)

phosphoric acid hexamethyltriamide (HMPA)

$$\text{C}_{18}\text{H}_{54}\text{X}_3\text{GdN}_9\text{O}_3\text{P}_3 = \text{Gd}[\text{HMPA}]_3\text{X}_3$$
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.2. Rare-earth elements-loaded PMMA-based PSs

Experimental samples:
diameter — 3 cm, height — 1 cm.
Mass fraction of gadolinium: 1%, 2% and 3%

- 2,5-Diphenyloxazole (PPO)
- 1,4-Di-(5-phenyl-2-oxazolyl)benzene (POPOP)
### 3. Organic scintillators in the JINR Laboratory of Nuclear Problems

#### 3.2. Element-loaded scintillators

#### 3.2.2. Rare-earth elements-loaded PMMA-based PSs

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Mass fraction of gadolinium, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>1.172</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.480</td>
</tr>
<tr>
<td>Number of Gd atoms per cm³, ×10²²</td>
<td>0</td>
</tr>
<tr>
<td>Number of H atoms per cm³, ×10²²</td>
<td>5.41</td>
</tr>
<tr>
<td>Number of C atoms per cm³, ×10²²</td>
<td>3.82</td>
</tr>
<tr>
<td>( \lambda_{max} ) of luminescence, nm</td>
<td>424</td>
</tr>
<tr>
<td>Transparency* (( \lambda_{max} )), %</td>
<td>82.8</td>
</tr>
<tr>
<td>Light output, %</td>
<td>100</td>
</tr>
<tr>
<td>Thermal neutrons (E ≤ 0.5 eV) detection efficiency, %</td>
<td>0</td>
</tr>
</tbody>
</table>
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.2. Rare-earth elements-loaded PMMA-based PSs

![Graph](image inserted)

- **Gd-loaded PS**
- **Nd-loaded PS**

**Axes:**
- **Relative light output, %**
- **Mass fraction, %**
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.2. Rare-earth elements-loaded PMMA-based PSs
### 3. Organic scintillators in the JINR Laboratory of Nuclear Problems

#### 3.2. Element-loaded scintillators

#### 3.2.3. Gd-loaded LSs

<table>
<thead>
<tr>
<th>Phenylcyclohexane (PCH)</th>
<th>Tributyl phosphate (TBP)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td><strong>Composition</strong></td>
</tr>
<tr>
<td>C(<em>{12})H(</em>{16})</td>
<td>C(<em>{12})H(</em>{27})O(_4)P</td>
</tr>
<tr>
<td><strong>Boiling point, °C</strong></td>
<td><strong>Boiling point, °C</strong></td>
</tr>
<tr>
<td>238 – 240</td>
<td>289</td>
</tr>
<tr>
<td><strong>Flash point, °C</strong></td>
<td><strong>Flash point, °C</strong></td>
</tr>
<tr>
<td>98</td>
<td>120</td>
</tr>
<tr>
<td><strong>Melting point, °C</strong></td>
<td><strong>Melting point, °C</strong></td>
</tr>
<tr>
<td>5</td>
<td>-80</td>
</tr>
<tr>
<td><strong>Specific gravity, g/cm(^3)</strong></td>
<td><strong>Specific gravity, g/cm(^3)</strong></td>
</tr>
<tr>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Index of refraction</strong></td>
<td><strong>Index of refraction</strong></td>
</tr>
<tr>
<td>1.525 – 1.527</td>
<td>1.422 – 1.423</td>
</tr>
<tr>
<td><strong>Scintillation efficiency, relative to toluene</strong></td>
<td><strong>Scintillation efficiency, relative to toluene</strong></td>
</tr>
<tr>
<td>1.02</td>
<td>–</td>
</tr>
</tbody>
</table>

3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.3. Gd-loaded LSs

- mixed solvent: PCH (60%vol.) + TBP (40%vol.);
- primary additive – PPO (0,5%);
- light shifter – POPOP (0,01%);
- Gd-containing additive – Gd[HMPA]$_3$Cl$_3$ (0,1% Gd)

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Light output, relative to anthracene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded</td>
<td>50%</td>
</tr>
<tr>
<td>0,1% Gd-loaded</td>
<td>46% (52%*)</td>
</tr>
</tbody>
</table>

*After O$_2$ removing.
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.3. Gd-loaded LSs

- **α-Methylnaphthalene (alpha-MN)**
  - Flash point - 82 °C

- **Tributylphosphate**
  - Flash point - 120 °C

- **2-(-biphenylyl)-5-phenyloxazole (BPO)**

- **Gd(NO₃)₃ x 6H₂O**
  - Gadolinium nitrate
### 3. Organic scintillators in the JINR Laboratory of Nuclear Problems
#### 3.2. Element-loaded scintillators
##### 3.2.3. Gd-loaded LSs

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Concentration of gadolinium, mg/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point, °C</td>
<td>245 245 245 245 245</td>
</tr>
<tr>
<td>Flash point, °C</td>
<td>&gt; 82 &gt; 82 &gt; 82 &gt; 82 &gt; 82</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>0.99 1.02 1.07 1.09 1.12</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.500 1.503 1.508 1.515 1.520</td>
</tr>
<tr>
<td>Number of Gd atoms per cm³, ×10⁵²²</td>
<td>0 0.0066 0.0196 0.0236 0.0328</td>
</tr>
<tr>
<td>( \lambda_{\text{max}} ) of luminescence, nm</td>
<td>395 397 398 398 400</td>
</tr>
<tr>
<td>Transparency* ( ( \lambda_{\text{max}} )), %</td>
<td>47.5 54 54.5 53.6 55.8</td>
</tr>
<tr>
<td>Light output, %</td>
<td>100 67 41 37 26</td>
</tr>
</tbody>
</table>

* Quartz cell, length — 5 cm, relative to air
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
3. Organic scintillators in the JINR Laboratory of Nuclear Problems

3.2. Element-loaded scintillators

3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment
3. **Organic scintillators in the JINR Laboratory of Nuclear Problems**

3.2. **Element-loaded scintillators**

3.2.4. **Gd-loaded LS for DAYA BAY neutrino experiment**
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment

Composition:

Solvent – LAB;

Primary additive – PPO (3g/L);

Wave shifter – bis-MSB (15 mg/mL);

Gd-containing additive – Gd(TMHA)$_3$ (0.1% Gd)

TMHA: 3,3,5-trimethylhexanoic acid
3. Organic scintillators in the JINR Laboratory of Nuclear Problems

3.2. Element-loaded scintillators

3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment

\[ \text{GdCl}_3 \times 6\text{H}_2\text{O} + 3\text{NH}_4\text{TMHA} \rightarrow \text{Gd(TMHA)}_3 \times 3\text{H}_2\text{O} + 3\text{NH}_4\text{Cl} + 3\text{H}_2\text{O} \]

Two methods

- **IHEP (Beijing) technology:**
  - the synthesis of the solid Gd-additive in water medium

- **BNL technology:**
  - water-organic extraction
3. **Organic scintillators in the JINR Laboratory of Nuclear Problems**

3.2. **Element-loaded scintillators**

3.2.4. **Gd-loaded LS for DAYA BAY neutrino experiment**

Water solution of $\text{GdCl}_3 \times 6\text{H}_2\text{O}$

Water solution of $\text{NH}_4\text{TMHA}$

**IHEP technology:**

the synthesis of the solid Gd-additive in water medium
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment

- Water solution of GdCl$_3$×6H$_2$O
- Water solution of NH$_4$TMHA

**BNL technology:**
water-organic extraction
3. Organic scintillators in the JINR Laboratory of Nuclear Problems
3.2. Element-loaded scintillators
3.2.4. Gd-loaded LS for DAYA BAY neutrino experiment

<table>
<thead>
<tr>
<th>Height of the sample, cm</th>
<th>Total registration efficiency, %, for $E_n &lt; 0.4$ eV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gd-LS</td>
</tr>
<tr>
<td>1</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>2</td>
<td>19 ± 3</td>
</tr>
<tr>
<td>3.5</td>
<td>29 ± 4</td>
</tr>
<tr>
<td>4.5</td>
<td>35 ± 5</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between height of the sample and total registration efficiency.]