Development of silicone rubber-based scintillators for different particles recording

Kuleshov D.A.[1], Kurinov K.O.[1], Maliy I.O.[1,2], Stenkin Yu.V.[1,2]

[1] Institute for Nuclear Research, RAS [2] Moscow Institute of Physics and Technology

Abstract: In our work we investigate specialized scintillators based on locally produced powdered phosphors immersed in an optically transparent silicone rubber. Scintillators of this type can be optimized for recording different types of particles. We present the results of studies of silicone rubber-based scintillators response to atmospheric muons, fast neutrons and radioactive background, mainly represented by the radon decay chain.

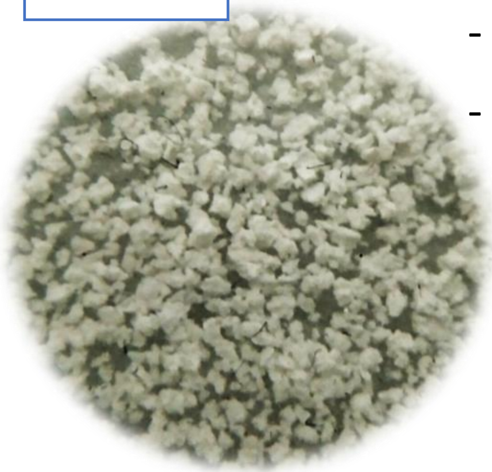
The aim of this work is to develop new, efficient, and cost-effective dispersed scintillators based on well-known ZnS-based phosphors produced in Russia and an optically transparent silicone compound [**1**], tailored for specific tasks in a wide range of nuclear physics experiments for recording of charged particles, gamma rays, and neutrons.

supported by the Russian Science Foundation (grant 24-22-00339)

Previous type of silicone rubber-based scintillator with natural boron (**LRB-2**)

Experiments: ENDA-LHAASO in China, its prototype **ENDA-INR**, INR RAS [**2**]
URAN, MEPhI

LRB-2



Components:

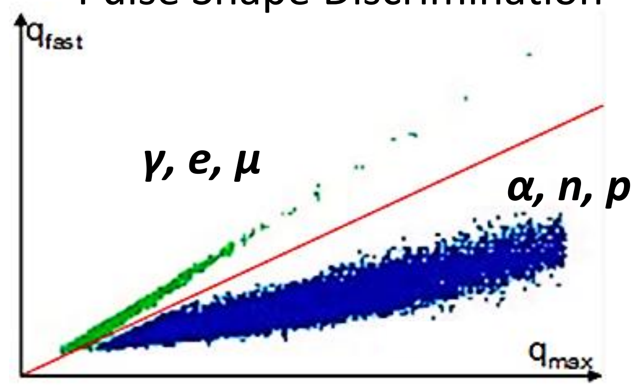
- High optical transparency **silicone** $[C_2H_6OSi]_n$ WACKER ELASTOSIL®)
- **ZnS(Ag)+B_2O_3** (50 mg/cm^2) phosphor powders from "RPF "Luminofor" Corp."[**3**]

$$^{10}B + n \rightarrow {}^{7}Li + \alpha + 2{,}792\ MeV \quad (6\%)$$
$$^{10}B + n \rightarrow {}^{7}Li^* + \alpha + 2{,}31\ MeV \quad (94\%)$$
$$^{7}Li^* \rightarrow {}^{7}Li + \gamma + 482\ keV$$

Why ZnS(Ag)

- several decay time components from ~40 ns and up to 100 µs.[**4,5**]
- one of the highest light yields (95,000 photons/MeV)
- quenching factor (α/e) ~ 1.0 and even more
  (with long decay time components)
- high radiation resistance

Pulse Shape Discrimination



Due to multiple decay time components in ZnS, we can distinguishing signals from light (***γ, e, μ***) and heavy (***α, n, p***) charged particles based on pulse shape, which is not possible with plastic scintillators.

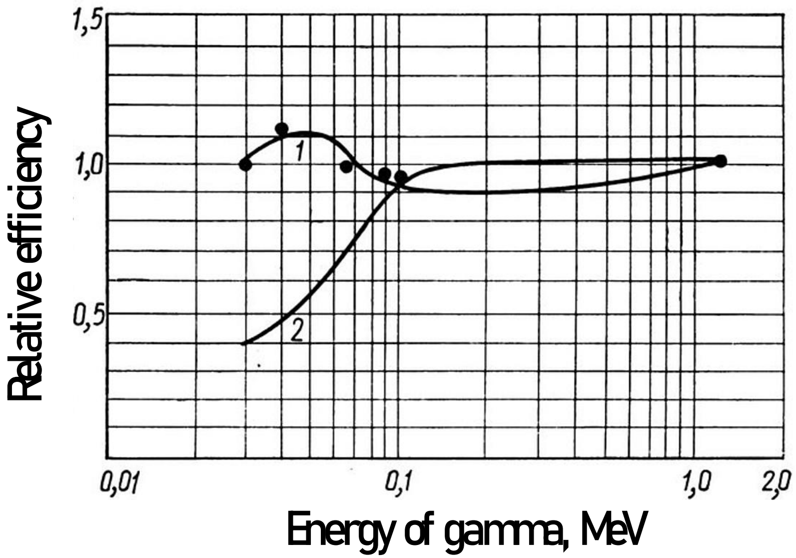
Variants of dispersed scintillators with different luminophores and optical compounds

One of the early references to **dispersed scintillators** for ***γ***-radiation dosimetry is discussed in [**6**](1969)

Dispersed scintillator consisted of plastic scintillator and ZnS(Ag) (K-430 phosphor).

The authors conclude that adding ZnS(Ag) phosphor powder to plastic can significantly improve the dosimetric properties of the plastic and create a detector suitable for gamma radiation dosimetry.

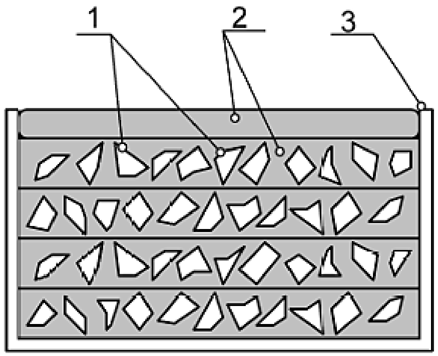
Comparison of the efficiency of dispersed scintillator and anthracene.



1 – dispersive detector with ZnS(Ag) and plastic
2 – anthracene (thickness 0,6 cm)
curve – calculation, points – experiment

The experimentally measured ratio of conversion efficiency of the scintillator with 1/200 of ZnS(Ag) and plastic scintillator $\eta_{ZnS}/\eta_{plastic}$ = **4,1**

In this work [7] dispersed scintillators are used as a **thermal neutron detector**.
^{6}**Li**-glass is used as a phosphor with various optical compounds: silicone, acrylic resin and epoxy resin.



1 – granules of ^{6}**Li**-glass
2 – optical compound
3 – highly reflective shell

Dispersed (heterogeneous) scintillators with 35% ^{6}**Li**-glass and silicone compound

The composite scintillators developed at JINR demonstrated a neutron-gamma discrimination level two orders of magnitude higher than that of homogeneous lithium glass (NE 912).

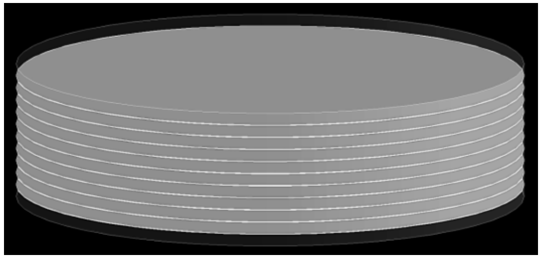
Advantages: - high neutron detection efficiency (91%) due to high ^{6}**Li** content (~9%) at 2 mm thickness
- good transparency compared to $^{6}LiF/ZnS(Ag)$
- short decay time (50-60 ns)

But one of the main problems of lithium glass is its very low light yield.
^{6}**Li**-glass (NE 912) light yield for electrons 3257 photons/MeV, for neutron capture 1048 photons/MeV, while B_2O_3/ZnS about 80000 photons/MeV.

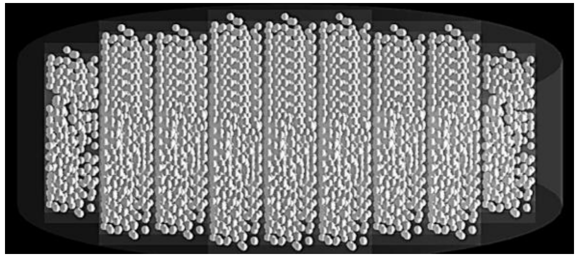
Due to the high hydrogen content in the silicone rubber-based scintillators (six H atoms per molecule fragment), it is possible to register ***fast neutrons*** (by recoil protons), and registration of ***thermal neutrons*** is possible by adding Boron or Lithium in this type of dispersed scintillators.

Neutrons detection by dispersed silicone rubber-based scintillators

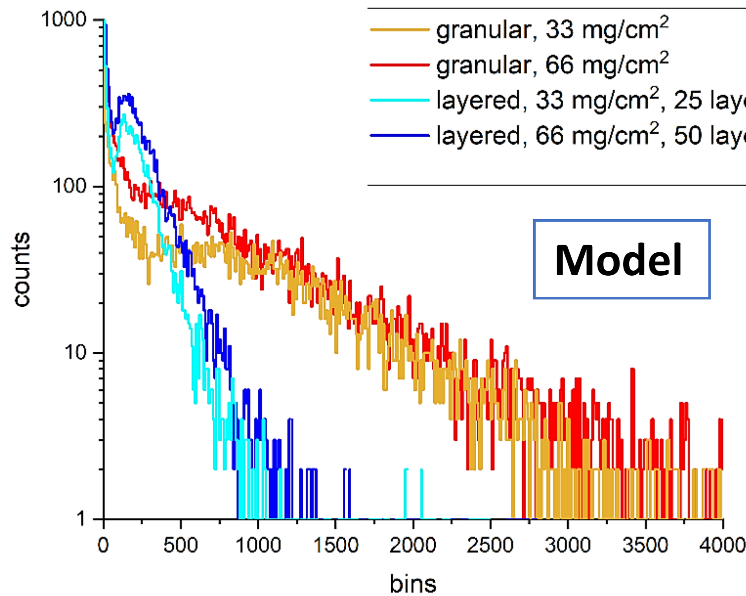
Developed **Geant4 models** of our dispersed scintillator [**8**]



Simple model with ZnS layers



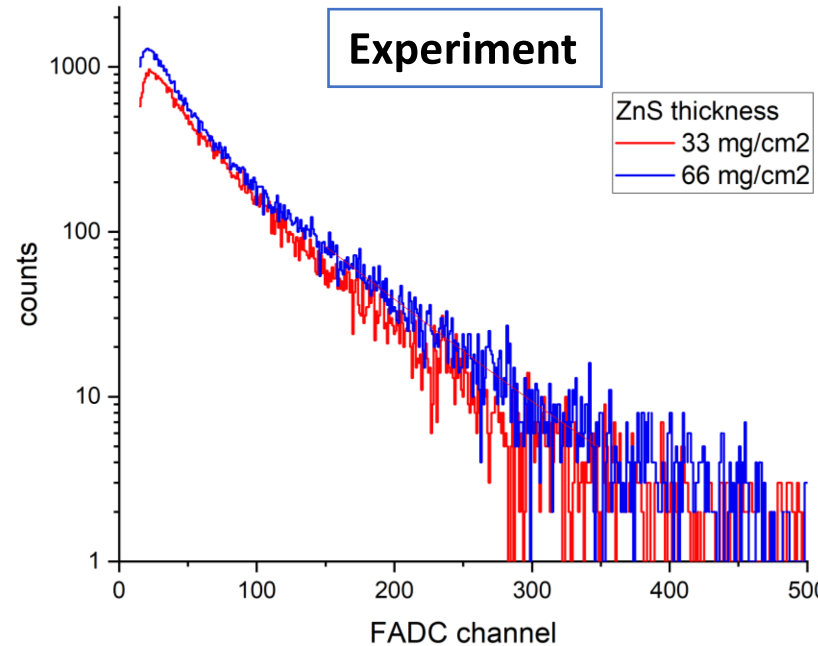
Realistic model with ZnS granules



Comparison of light collection in the “granular” and “layered” models of silicone scintillator with **Cf252** source.

«Realistic» light propagation model: real **r**-indices of ZnS and silicone, ***unified model*** for granule surface, the boundary type was ***dielectric_dielectric***, the surface type was ***ground***.

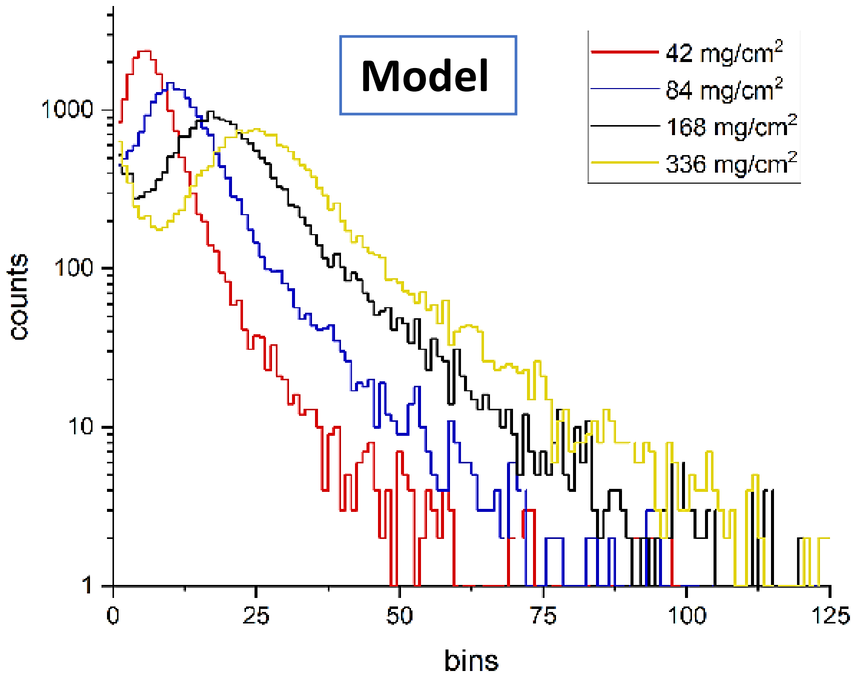
Pulse height distributions of signals from silicone scintillator (3 mm thick, RS-450 phosphor) with a fast neutron source **Cf-252**.



With knowing the neutron flux from the **Cf252** source, we obtained a registration efficiency of about **1%**.

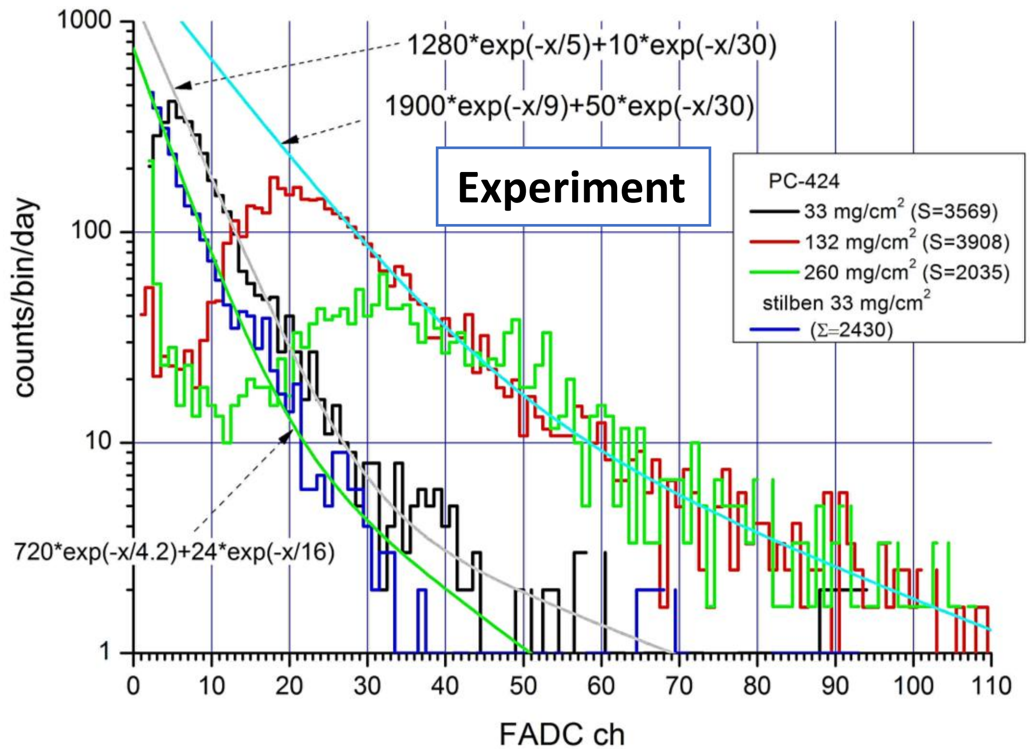
Atmospheric muons detection by silicone rubber-based scintillators

Light collection from atmospheric muons in the “granular” model of silicone scintillator



Geant4 photon tracing with “Mie” optical model (Henyey-Greenstein scattering)

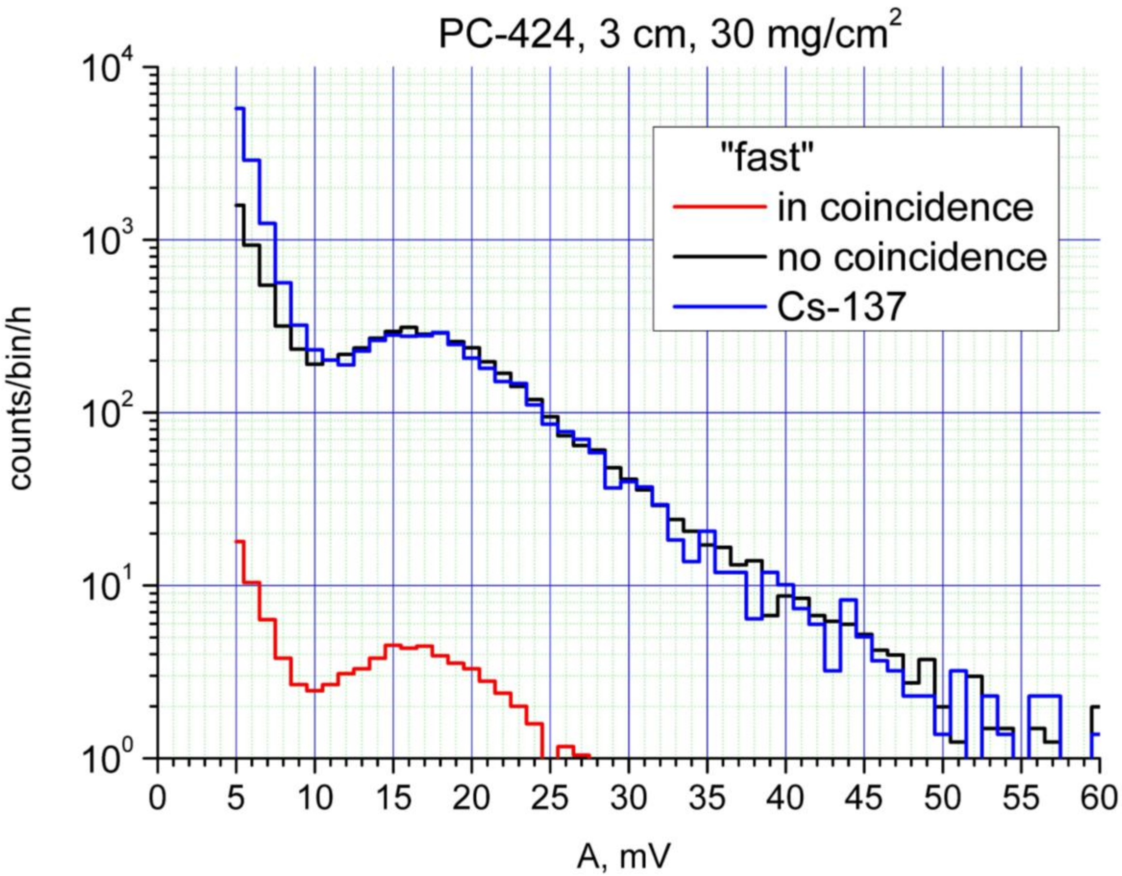
Pulse height distributions of silicone scintillator (2 cm thick) signals from atmospheric muons.



Daily spectra for ZnS(Ag) (RS-424 phosphor) and stilbene with various scintillator thicknesses

As ZnS(Ag) thickness increases, the muon peak shifts to the right, but the peak-to-valley ratio becomes worse.

Atmospheric muons detection by silicone rubber-based scintillators



Pulse height distributions of silicon scintillator signals from atmospheric muon in coincidence and non-coincidence mode, and with a Cesium-137 gamma-quantum source.

In addition to the clearly visible atmospheric muon peak (even without coincidences), sensitivity to gamma quanta is also noticeable (due to the relatively high atomic number of Zn and S).

In the graph, the experimental data show a much better peak-to-valley ratio for muons with a significantly lower ZnS thickness (**only 30 mg/cm²**).

This is due to the much larger number of direct photons (ballistic photons) that reach the photodetector immediately after scintillation in ZnS(Ag), bypassing scattering by a large number of ZnS(Ag) granules.

Conclusions:

- Dispersed silicone scintillators based on domestically produced ZnS phosphors and a silicone compound are presented, suitable for detecting various types of particles (fast and thermal neutrons, muons, and gamma rays).
- Due to ZnS multiple decay time components in silicone scintillators, it is possible to separate signals from fast particles (gamma quanta, electrons, muons, etc.) and from heavy, slowly moving particles (alpha, tritons, protons) by pulse shape discrimination.
- With a large number of hydrogen atoms in the silicone molecule, dispersed silicone scintillators can effectively register fast neutrons using recoil protons, as well as register thermal neutrons with the addition of neutron capturers (Boron, Lithium).
- Possibility of recording an atmospheric muon peak using silicone scintillators even without a coincidence mode has been experimentally demonstrated.
- Geant4 model of a silicon scintillator is being developed using a photon tracking procedure.
- Optimizing of dispersed silicon scintillators continues, in particular the selection of ZnS granules size and the thickness of the scintillator.

References:

1. D.A. Kuleshov, Yu.V. Stenkin and all., Bull. of the Russ. Acad. of Sci.: Phys., Vol. 89, issue 6, 2025.
2. Stenkin Yu.V., Nuclear Track Detectors: Design, Methods and Applications. Nova Sci. Publish. **10**, 253 (2010).
3. https://luminophor.ru/catalog/lyuminofory/radiolyuminofory/stsintillyatory/
4. Asada T., Masuda M., Okumura M., Okuma J., J. Phys. Soc. Jpn. **14**, 1766 (1959).
5. Carel W.E. van Eijk, Nucl. Instr. and Meth. A. **460**(1), 1 (2001).
6. S.P. Vershinina, G.P. Volosyuk, Yu.A. Tsirlin & M.A. Strzhemechny, Soviet Atomic Energy, Vol. 26, p. 386–390, (1969).
7. Ilya Zimin, on the materials of the PhD thesis, https://indico.inr.ac.ru/event/5/contributions/167/
8. I.O. Maliy, on the materials of the master thesis.