Simulation and experimental study of GAGG:Ce detector of fast neutrons

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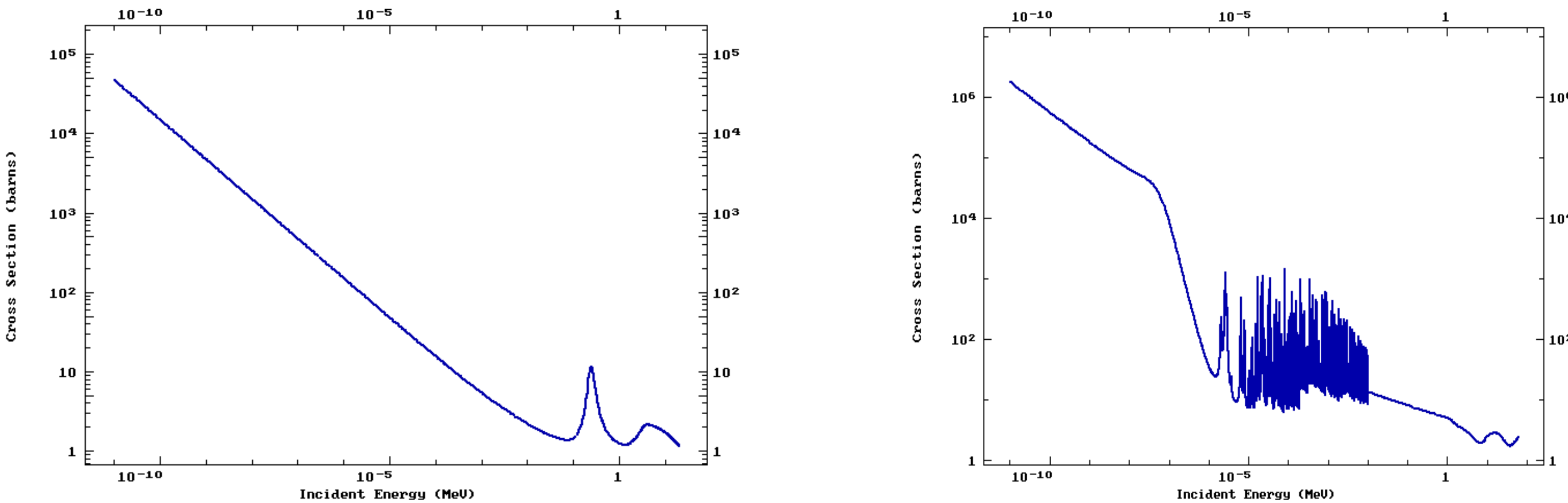
Natural mixture of gadolinium isotopes has the highest thermal neutron absorption cross section for all Re-elements - 49,000 barns. This also far exceeds that of ^{3}He, ^{6}Li, or ^{10}B nuclei used in neutron detection.



Neutron total cross sections of ^{6}Li isotope and natural mixture of Gd isotopes.
Evaluated Nuclear Data File (ENDF), https://www-nds.iaea.org/exfor/endf.htm

- The major reaction for thermal neutrons in gadolinium is radiation capture (n,ɣ), in which multiple gamma-quanta with total energy of about 8 MeV are emitted.
- Broad zone of resonances increases the neutron absorption efficiency for neutron energies from 1,0 eV to 10 keV.
- **Starting from ~ 55 keV of the neutron energy, the process of neutron inelastic scattering is accompanied by the gamma-quanta emission, forming soft lines in the resulting gamma-quanta spectrum.**

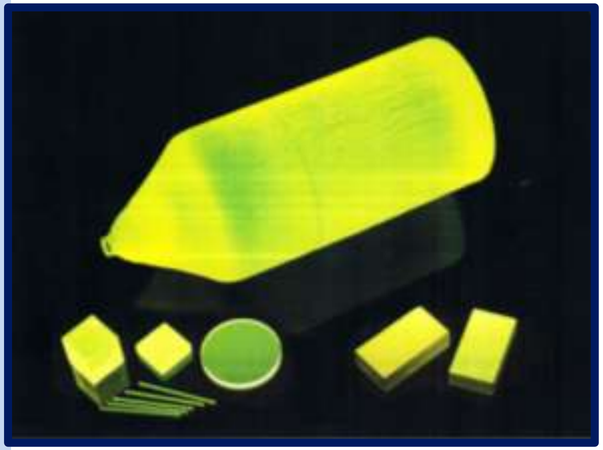
Gd-containing scintillation crystal

Gd foils or Gd-loaded plastics are well known in neutron detection. But Gd can form scintillation crystals and ceramics, such as GSO:Ce and GAGG:Ce, wich has better scintillation efficiency.
High density of such compounds plays positive role in gamma-ray absorption efficiency; however large atomic mass of Gd means less atoms per gram (many Barns per atom for fewer atoms).

The aim of this work is to study possibilities of Gd-based scintillator in neutron detection, and compare its sensitivity with Li-6 based one (Li-glass).

Gd-containing scintillation crystal

We modelled interaction of neutrons with 2 mm gadolinium metal plate (thick enough for positron thermalization) with GEANT 4.
In our experimental studies we used newest aluminum gallium garnet GAGG single crystals doped with Ce, Mg, Ti, as a scintillation material designed to overcome some drawbacks of solely Ce-doped and Ce, Mg co-doped GAGG crystals.

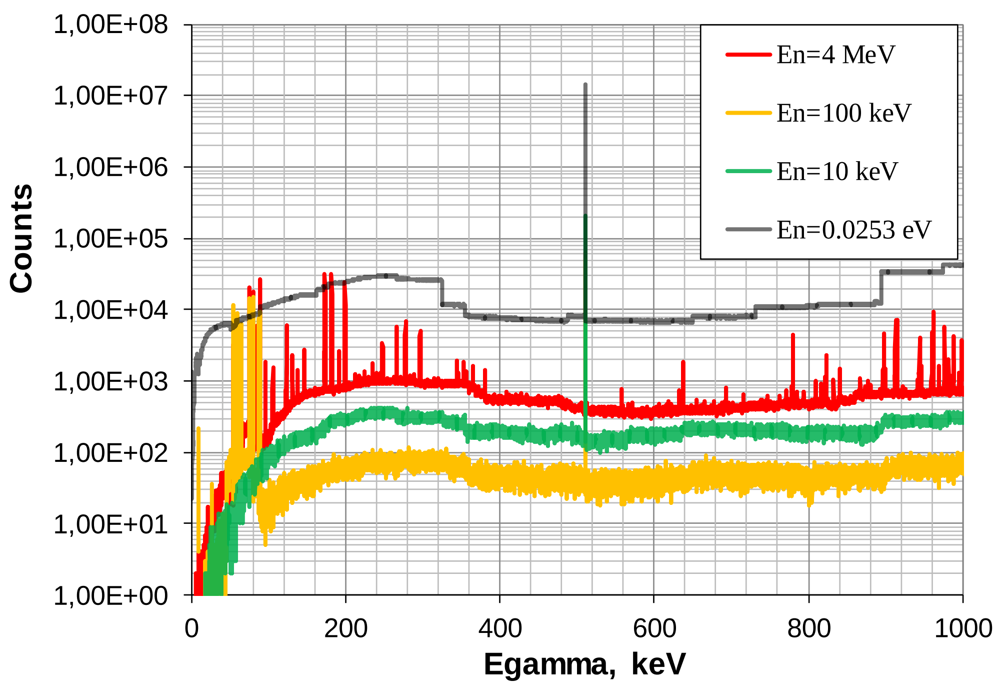


Main properties of GAGG:Ce, Mg, Ti are listed below.

Density, g/cm³	Z_{eff}	Emission maximum, nm	Light yield, ph/MeV	Decay kinetics, ns(%)	Energy resolution, % *	Time resolution (CTR), ps*
6.68	51	520	38000(RT) 46000(-45^{o}C)	30 (25%), 80 (60%), 100-200 ns (15%)	6,2%(511keV,-20^{o}C) 3,6%(1270keV, -20^{o}C)	170 (-20 to 20^{o}C)

**Small crystal samples coupled to a 4x4 mm SiPM*

Production of γ-quanta in Gd, simulation

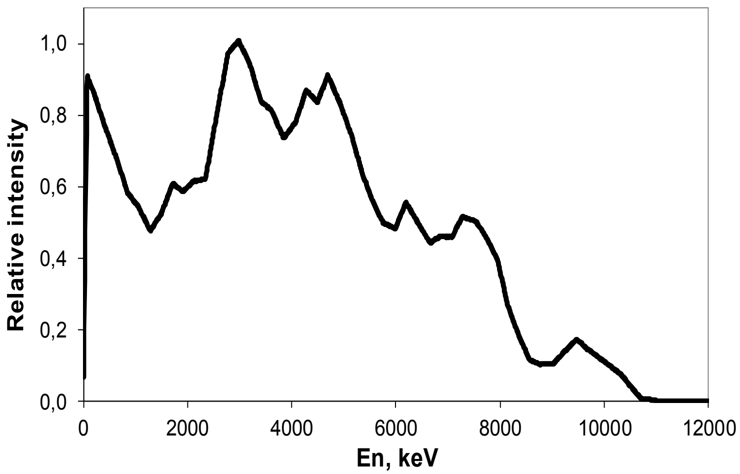


Spectra of the emitted gamma-quanta in metallic gadolinium with 2 mm thickness, irradiated with monochromatic neutrons in a broad energy range, simulated with GEANT4.

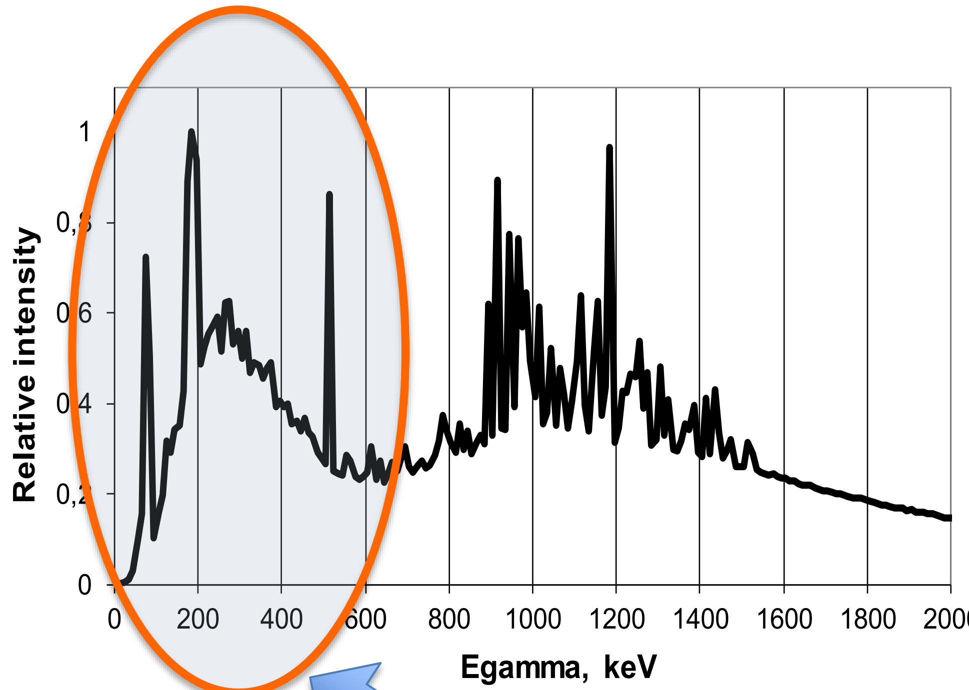
Results

- **511 keV annihilation gamma-line presents in all spectra at all neutron energies;**
- **There are no prominent soft γ-lines in the spectra for thermal neutrons (E_n = 0.0253 eV) and for neutrons with E_n <55 keV;**
- **Numerous gamma-lines present across all the gamma-spectrum for E_n > 1 MeV.**
- **Relative yield of at least several soft gamma lines depends on the incident neutron energy.**

GEANT4 modeled soft fraction of spectrum of γ-quanta born in 2 mm Gd metal plate, irradiated with fast neutrons from Am-Be source

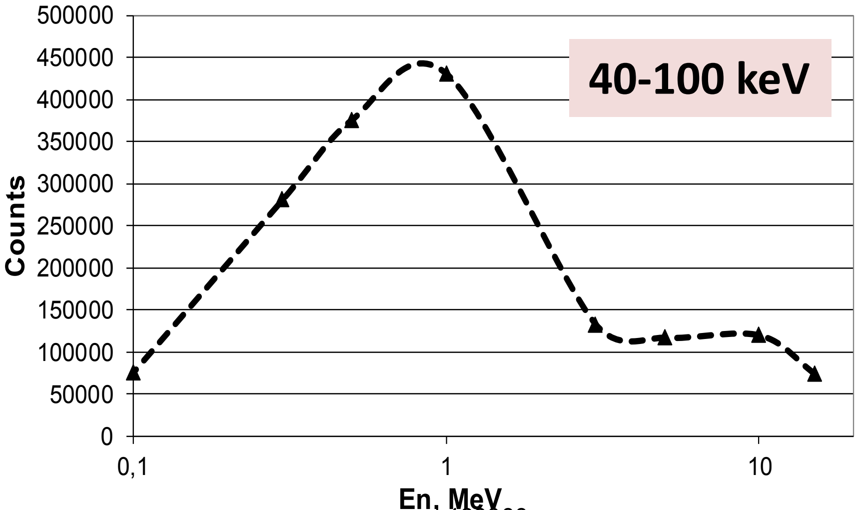


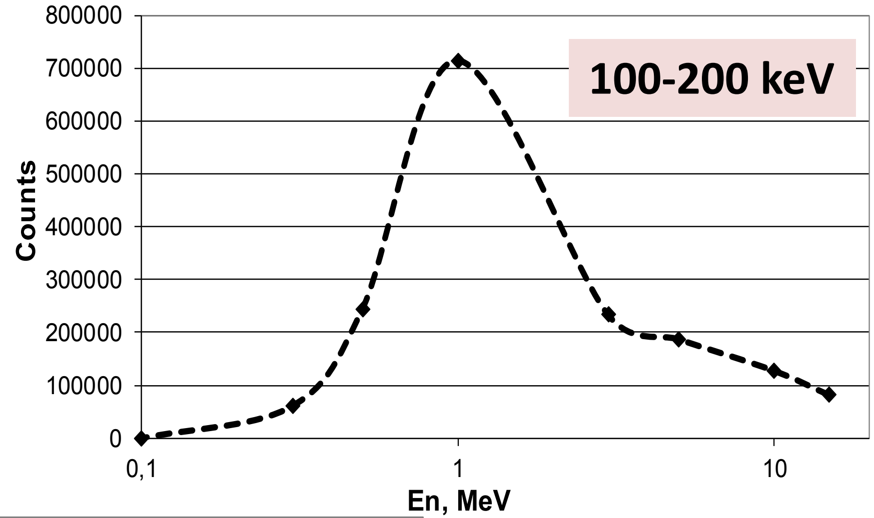
Spectrum of neutron energies from Am-Be neutron source, in accordance with ISO 8529-1:2001(E)

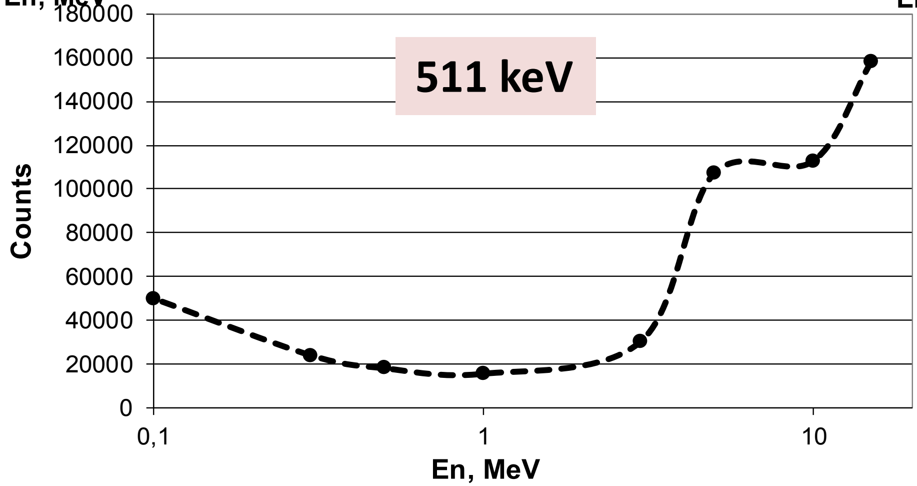


Range of main interest: ~90 keV, ~190 keV, 511 keV lines

GEANT4 simulated yield of γ-lines in 40-100 keV, 100-200 keV energy ranges and for 511 keV line versus neutron energy, from E_n=100 keV to E_n=15 MeV (lines area).



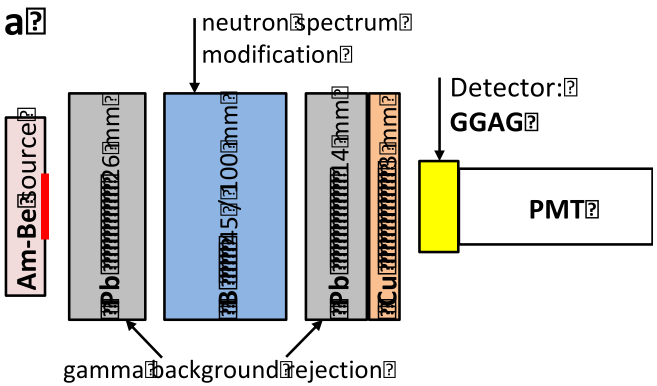


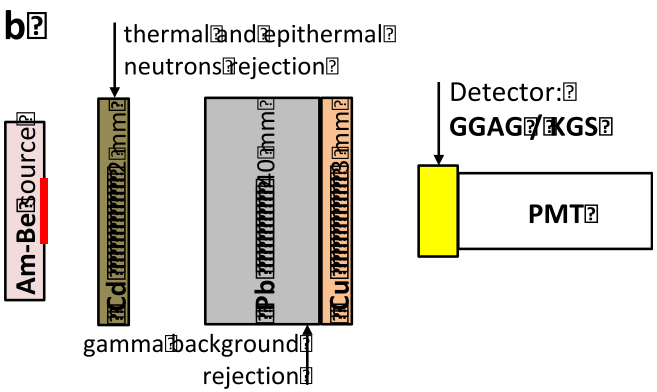


Layout of the measurements schemes

a- neutron spectrum transformation

b- sensitivity comparison





SAMPLES

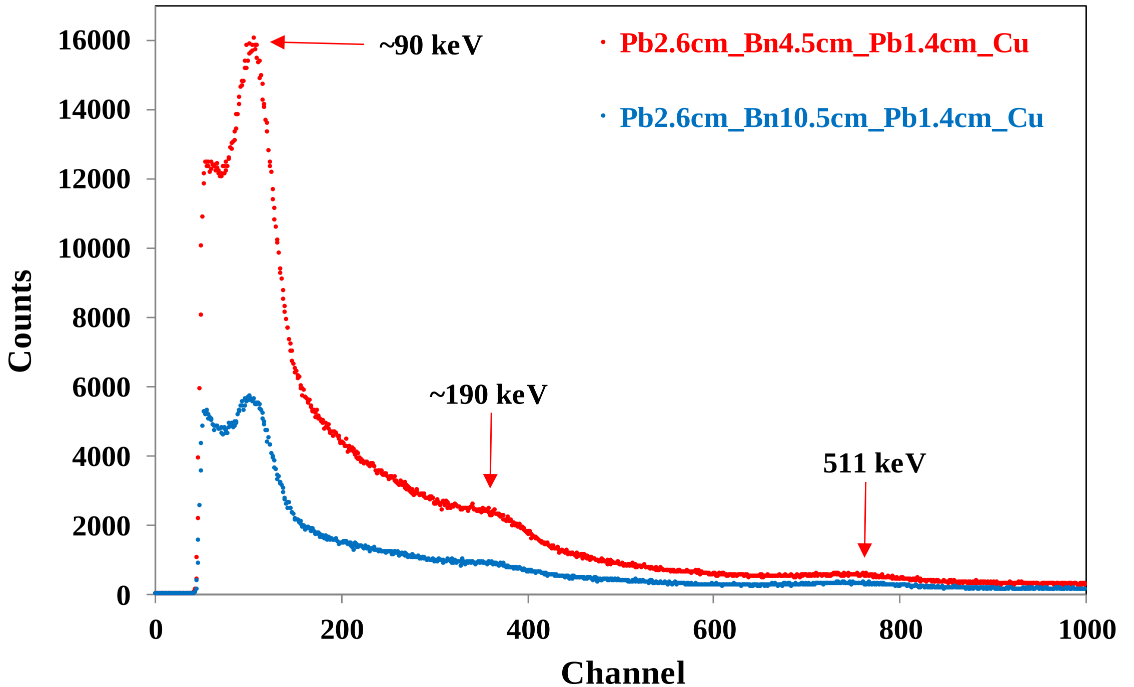
GAGG:Ce sample used was 15×18×7 mm size, surface area faced to neutron source 2.70 cm^2, volume 1.89 cm^3;

Li-glass with close dimensions was used for sensitivity comparison:

Li-based scintillator was a KGS-3 scintillation glass ceramics with ^{6}Li content close to that of well-known Saint Gobain scintillation glass GS-20 with size 18×18.5×4 mm, with surface area faced to neutron source of 3.33 cm^2, volume 1.33 cm^3

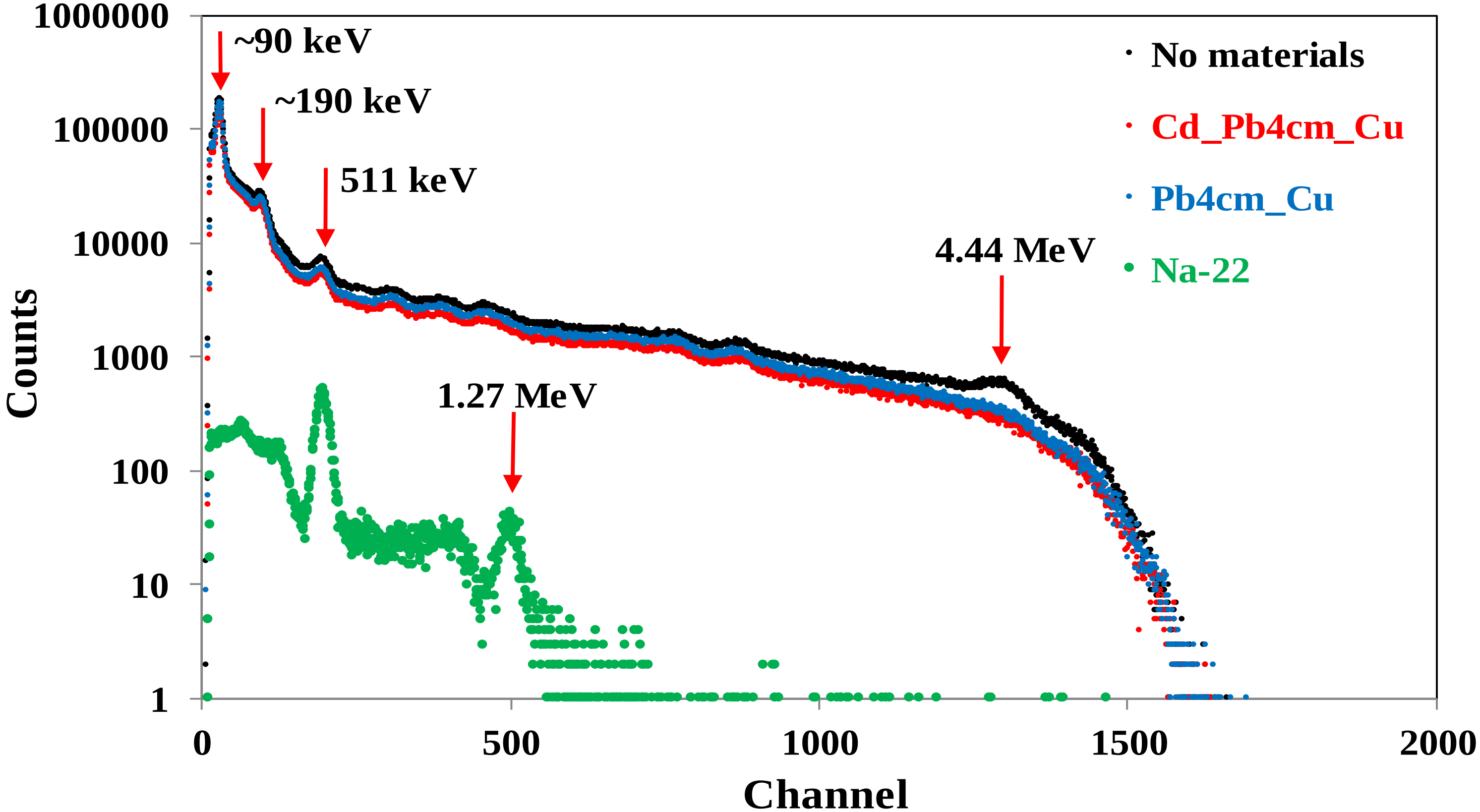
A. Nikitin, A. Fedorov, M. Korjik, Novel Glass Ceramic Scintillator for Detection of Slow Neutrons in Well Logging Applications. Nuclear Science, IEEE Transactions on 60 (2), 2013, pp. 1044-1048

Spectra of Am-Be source measured with GAGG:Ce 15×18×7 mm at different thicknesses of boron acid absorber

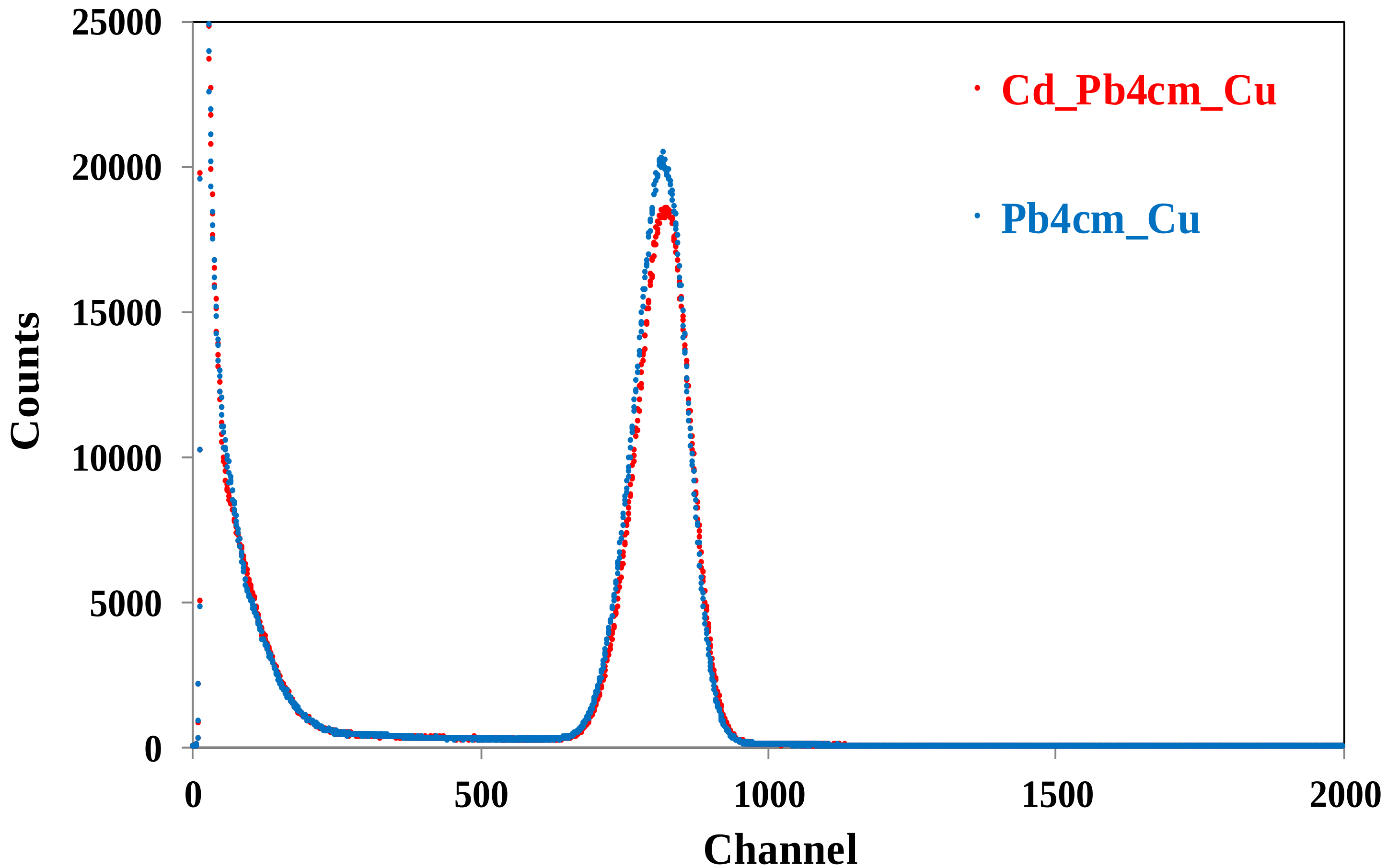


Increase of the boron acid absorber thickness from 4.5 cm to 10.5 cm transforms neutron source spectrum, which results in a decrease of the area of ~90 keV line in more than 4 times, while the area of 511 keV line decreases only by a factor of 2.

γ-spectra measured with GAGG:Ce 15×18×7 mm sample irradiated by neutrons from Am-Be source.



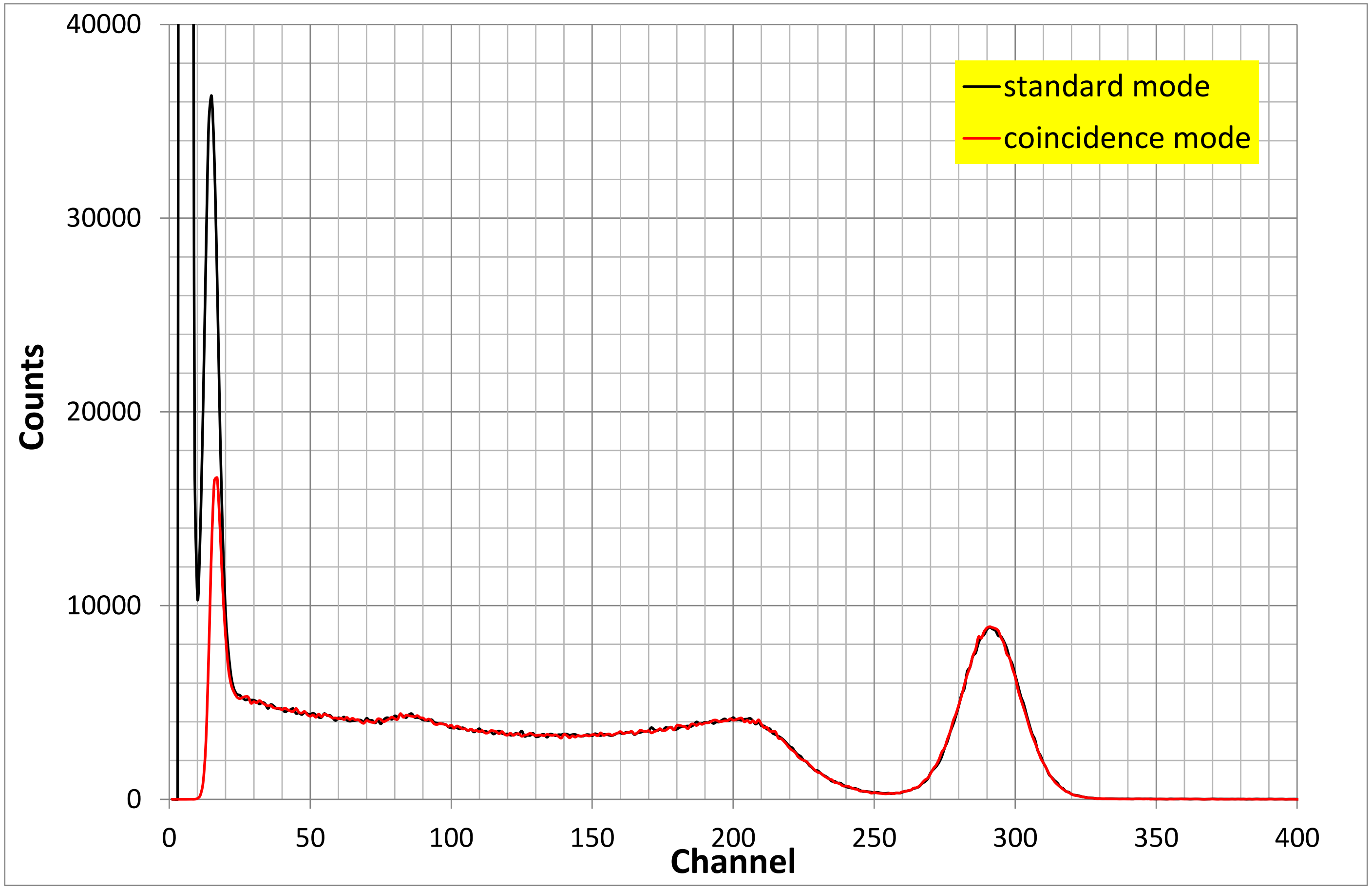
Neutron peak from Am-Be source centered in ~800 channel, recorded with KGS-3 scintillation glass.



Comparison of countrates measured with ^{6}Li KGS glass ceramics (neutron peak) and GAGG: Ce,Mg,Ti crystal (90, 190, 511 keV lines) in the same position relative to Am-Be source.

Detector	Lines area, counts		Count rate per volume, Count/s*sm^3
KGS-3 18x18,5x4 mm^3	Pb+Cu	Neutron peak - 2316180	**5805**
	Cd+ Pb+Cu	Neutron peak - 2161030	**5416**
GAGG:Ce 15×18×7 mm^3	Pb+Cu	~90 keV - 1255690	**2214**
		~190 keV - 143108	**252**
		511 keV - 42031	**74**
		Full spectrum - 7003420	**12352**
	Cd+ Pb+Cu	~90 keV - 1007870	**1778**
		~190 keV - 130794	**231**
		511 keV - 35352	**62**
		Full spectrum – 6154690	**10855**

Prototyping of GAGG:Ce,Mg,Ti neutron detector with SiPM matrix readout.



Conclusions

Our modeling and experimental evaluations have shown that gamma-spectra acquired with GAGG:Ce,Mg,Ti scintillation detector under neutron irradiation contain information on the incident neutron kinetic energy, which can be used, in particular, for neutron sources identification. Sensitivity of the GAGG:Ce,Mg,Ti detector with moderate size in a wide range of neutron energies was found to be comparable or superior to that of Li-glass scintillation materials, depending on the method of gamma-quanta counting.

In addition, GAGG:Ce,Mg,Ti does not require an enrichment with neutron sensitive isotopes, which makes it even more cost-effective in comparison with ^{3}He gas counters and ^{6}Li-containing inorganic scintillators.

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Thank you!!!