Fast neutron detection with GAGG/SiPM matrix detector

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Layout

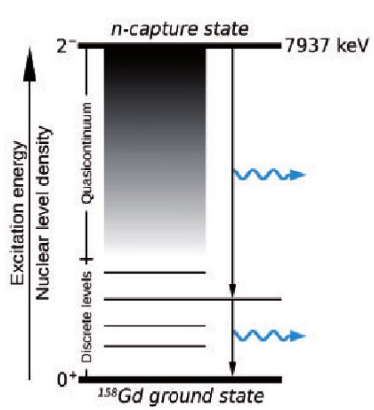
1. **Neutron detection with Gd-based inorganic scintillators**
2. **Garnet family of the scintillation materials**
3. **TOF capabilities with GAGG**
4. **PSD capabilities with GAGG**

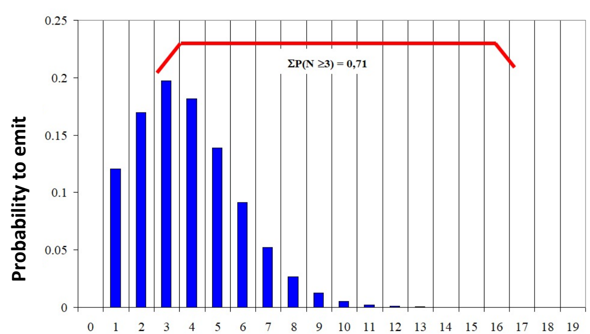
Advantages of GAGG for neutron detection

Isotope	Nuclear reaction	Natural isotope abundance, %	Thermal neutrons cross section, barn
^{3}He	$^{3}He + n \rightarrow {}^{3}H + p$	0.00014 Accumulated due to reaction: $^{3}_{1}H \rightarrow {}^{3}_{1}He + e^{-} + \nu_{e}$	5330
^{6}Li	$^{6}Li + n \rightarrow {}^{3}H + \alpha$	7.4	940
^{10}B	$^{10}B + n \rightarrow {}^{7}Li + \alpha$	19.8	3840
^{12}C	$^{12}C + n \rightarrow {}^{9}Be + \alpha$	98.93	3.4
^{155}Gd	$^{155}Gd + n \rightarrow {}^{156}Gd + \gamma$	14.8	60991
^{157}Gd	$^{157}Gd + n \rightarrow {}^{158}Gd + \gamma$	15.65	254840

$Gd_3Al_2Ga_3O_{12}$ scintillation properties	
Light yield, ph/MeV	43000
Decay time, ns	70
Density	6.68
Zeff	54.4
CTR with 511 keV, ps	160
Energy resolution 511 keV with SiPM readout, %	6-7

Due to high neutron cross section and brilliant scintillation properties, GAGG represents good candidate as a neutron detection material

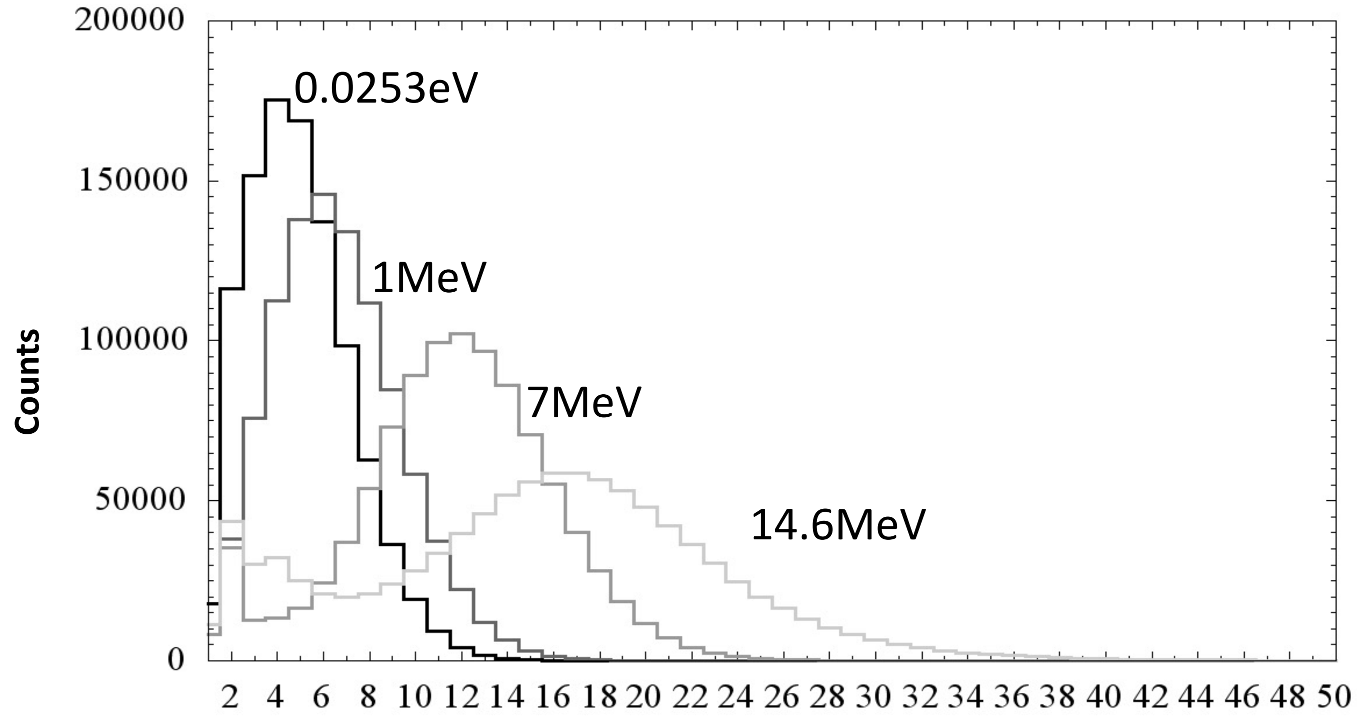




Distribution of the number of the emitted gammas for thermal neutrons

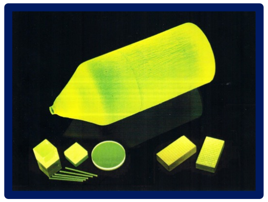
GAGG/SiPM response to Pu-Be neutron source

GEANT4 simulation of the distribution of the number of the emitted gamma-quanta in GAGG under neutrons of different energies.



Distribution of the number of the emitted gammas for neutrons of different energy

GAGG family of inorganic scintillation materials



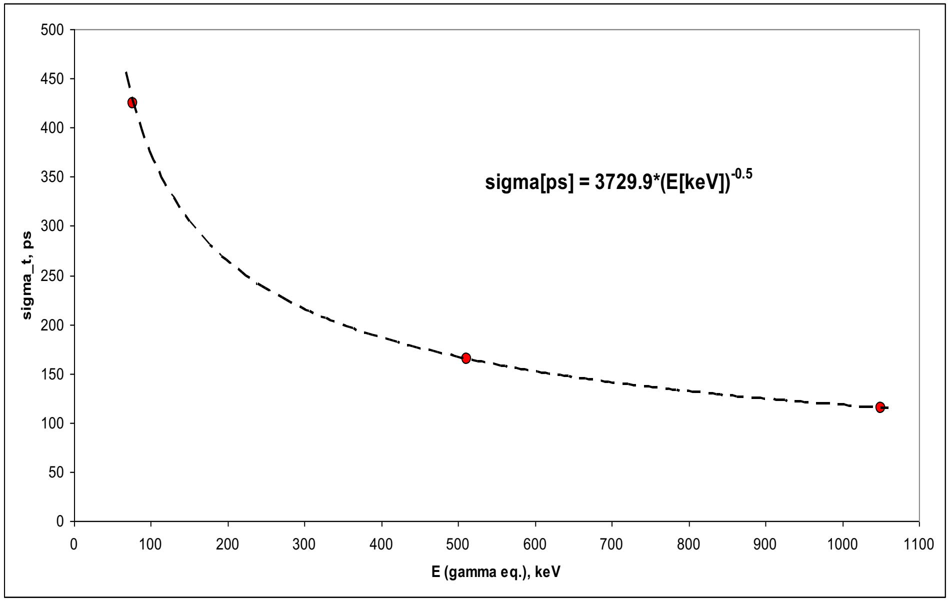
	GdLuAGG $(Gd,Lu)_3Al_2Ga_3O_{12}$:Ce	GYAGG $(Gd,Y)_3Al_2Ga_3O_{12}$: Ce,Mg	GAGG $Gd_3Al_2Ga_3O_{12}$: Ce,Mg
LY, ph/MeV	60000	50000	41000
Decay/fraction ns(%)	24 (60); 60 (30); 520 (10)	36 (80); 97 (20)	28 (30); 68 (52); 168 (18)
Radiation tolerance **γ-quanta** **hadrons**	🤓 Not studied	🤓 Not studied	🤓 🤓
Scintillation maximum, nm	508	510	520
CTR with 511keV and SiPM, ps	Not measured	112+/-5	160+/-5

Since the main channel for registering neutrons is low-energy γ-quanta, it is possible to use thin crystals for the E_n below a few MeV . This helps to solve the problem of n/γ discrimination as well.

Expected time resolution

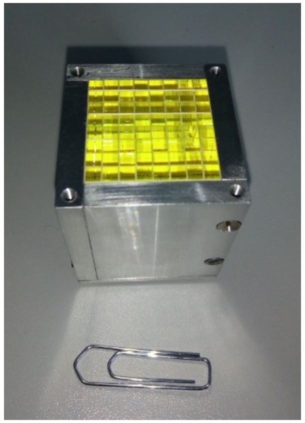
Sample	CTR FWHM, ps, at different temperatures		
	+20ºC	0ºC	-20ºC
GAGG multidoped	165±3	160±2	164±2

511 keV coincidence time resolution measured with RGB SiPMs (FBK) at different temperatures

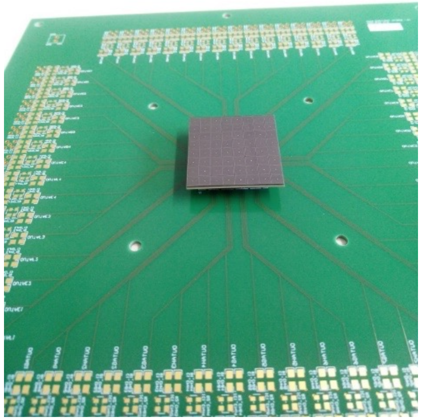


Time resolution is expected to be below 500 ps at the detection of the gamma-quanta with energy ~100 keV,whch are created by neutrons

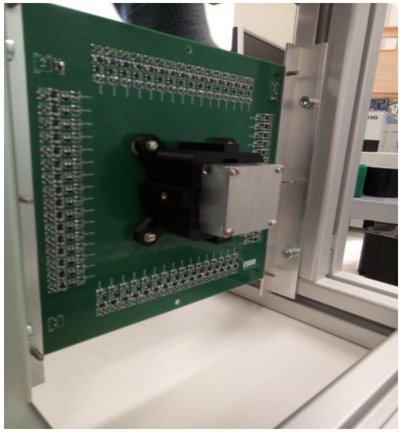
Detector prototype and measurements layout



GAGG matrix in aluminum holder



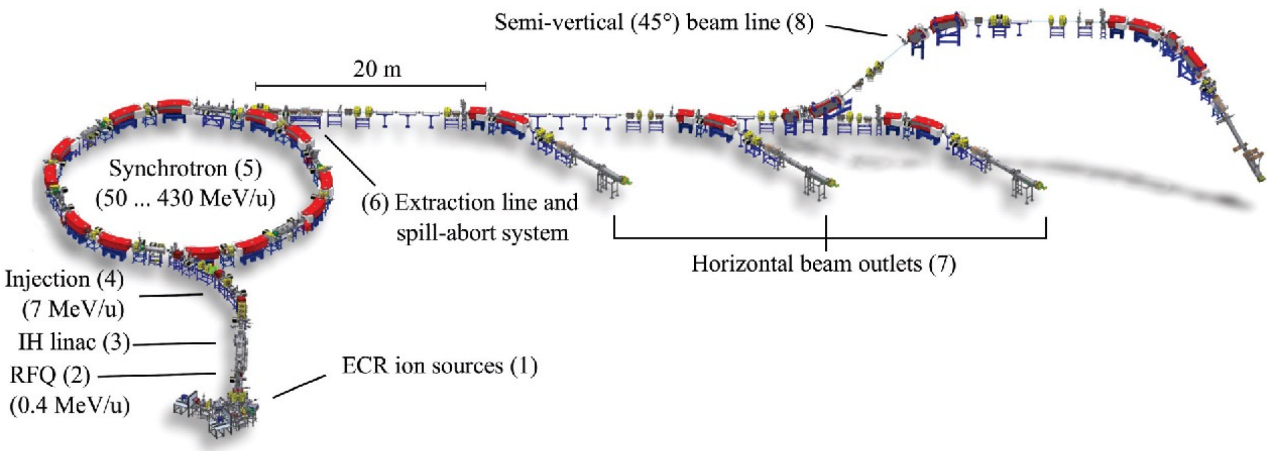
SiPM-amplifier coupling PCB



Prototype

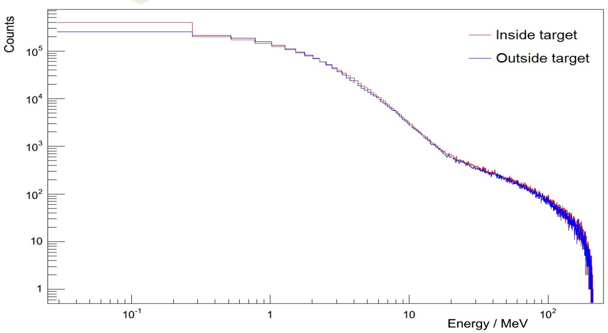
MIT @ Marburg Clinic

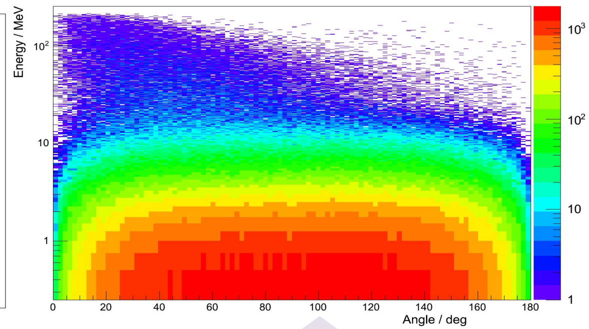
- proton beam 220 MeV
- average count rate 40-50 kHz
- Pb (p,xn) X : spectrum of neutrons in the energy range up to 200 MeV and γ-quanta up to 10 MeV



GEANT4 simulation

Neutron energy spectrum inside and outside the lead target 100x100x60mm under 220MeV protons

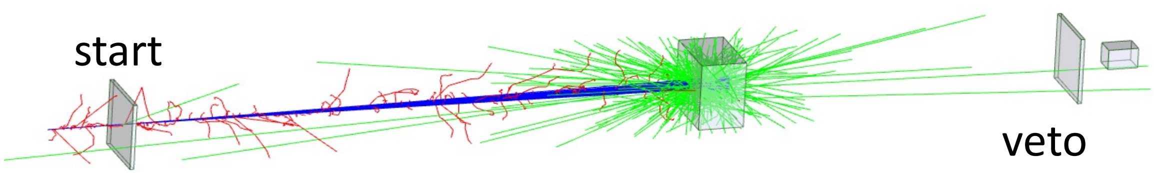


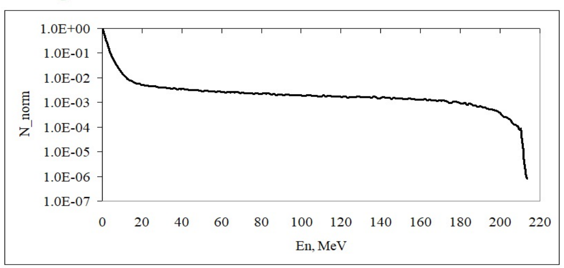


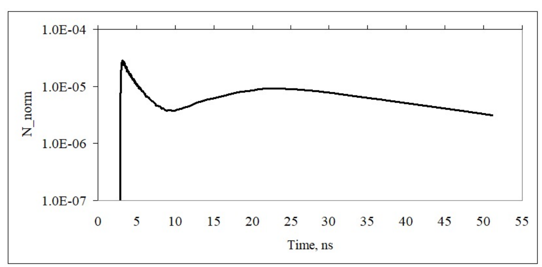
Distribution of neutrons by emission angles and energy outside the target

Estimated distance (L) from target (Pb) to detector for the neutrons discrimination
Number of primary protons $N_p = 10^7$

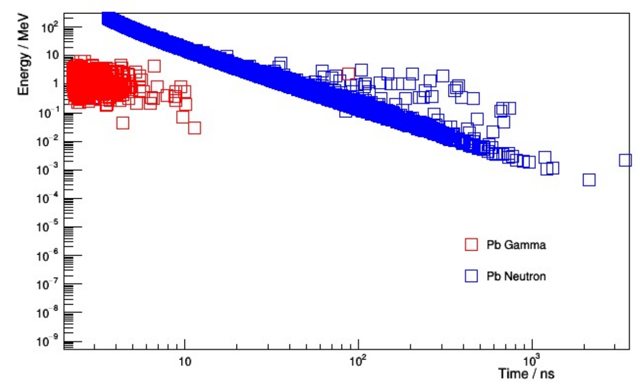
L, m	N_n	N_γ	N_{charge}	t_γ, ns	t_n, ns
0.25	25435	3838	67	1.5	2.5
0.5	7104	1105	18	2	4
1	1817	274	10	4	7
3	216	30	0	11.5	19.5





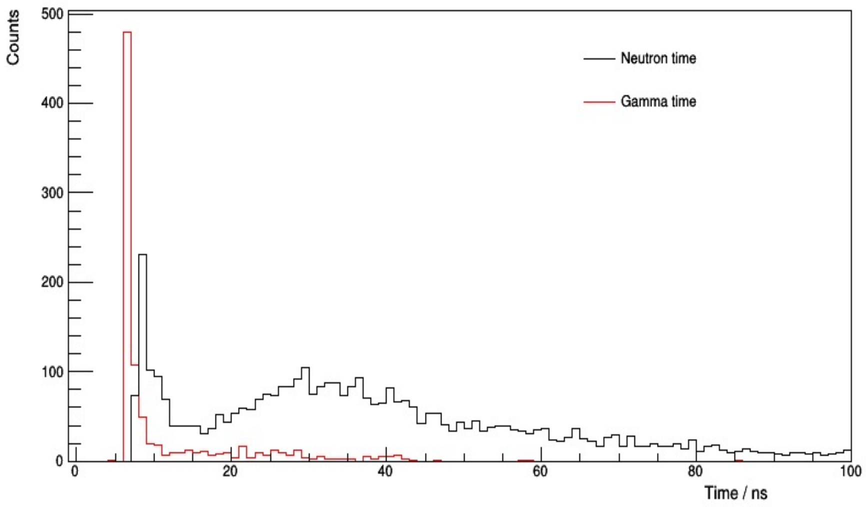


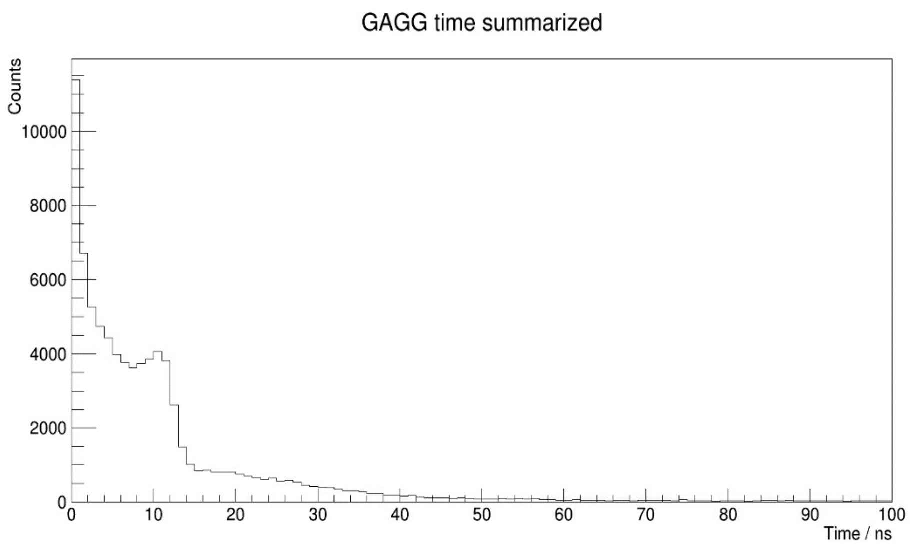
Energy spectrum (left) and time spectrum (right) of neutrons hitting the stop counter



Energy vs TOF dependence for 0.5 m distance

Simulation versus measurements

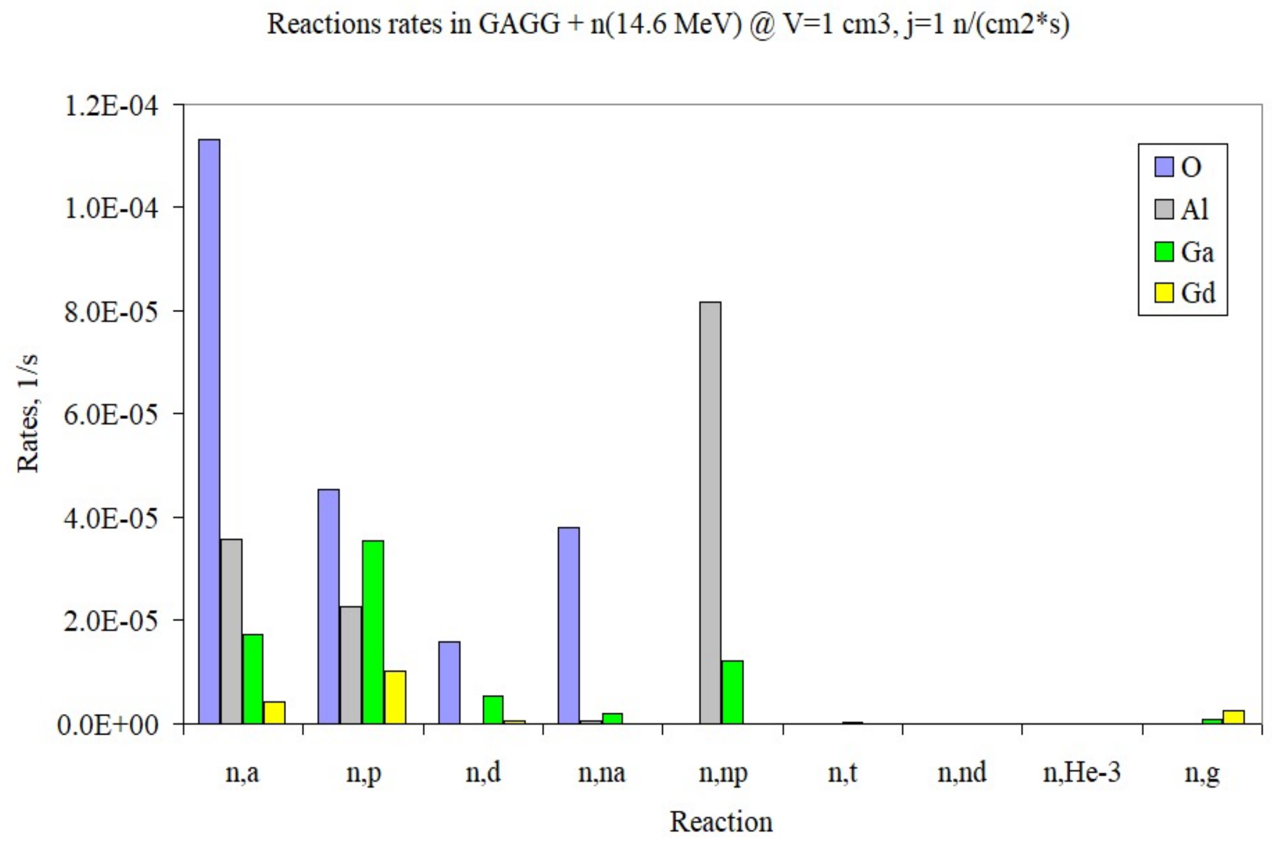




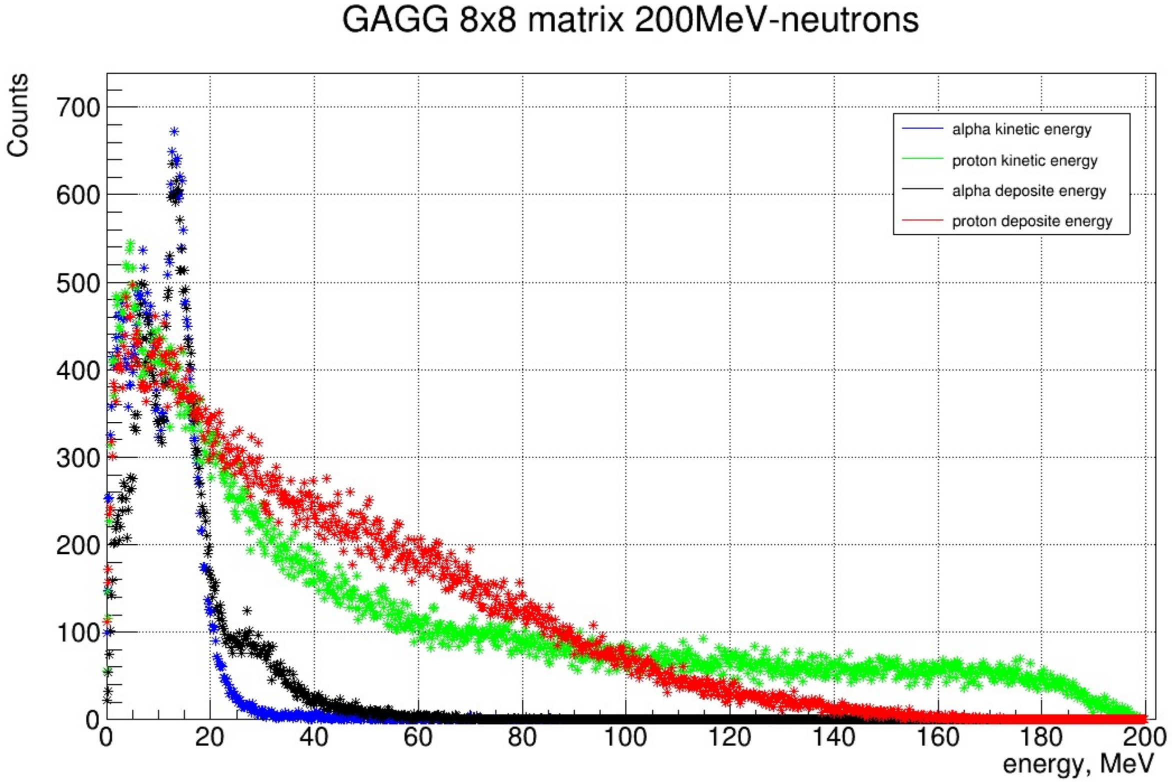
Time spectrum of neutrons and gamma-quanta recorded with GAGG detector, according to the simulation results (left) and the measured spectrum by the STOP(matrix) channel (right)

The resulting time spectrum demonstrates a structure similar to that obtained during the simulation with GEANT4: the presence of two peaks in the first 20 ns, which can be compared with the accompanying γ-quanta and fast neutrons.

Role of the light nuclei in GAGG for the fast neutron detection



Energy distribution of the products of the reactions of the high energy neutrons in GAGG

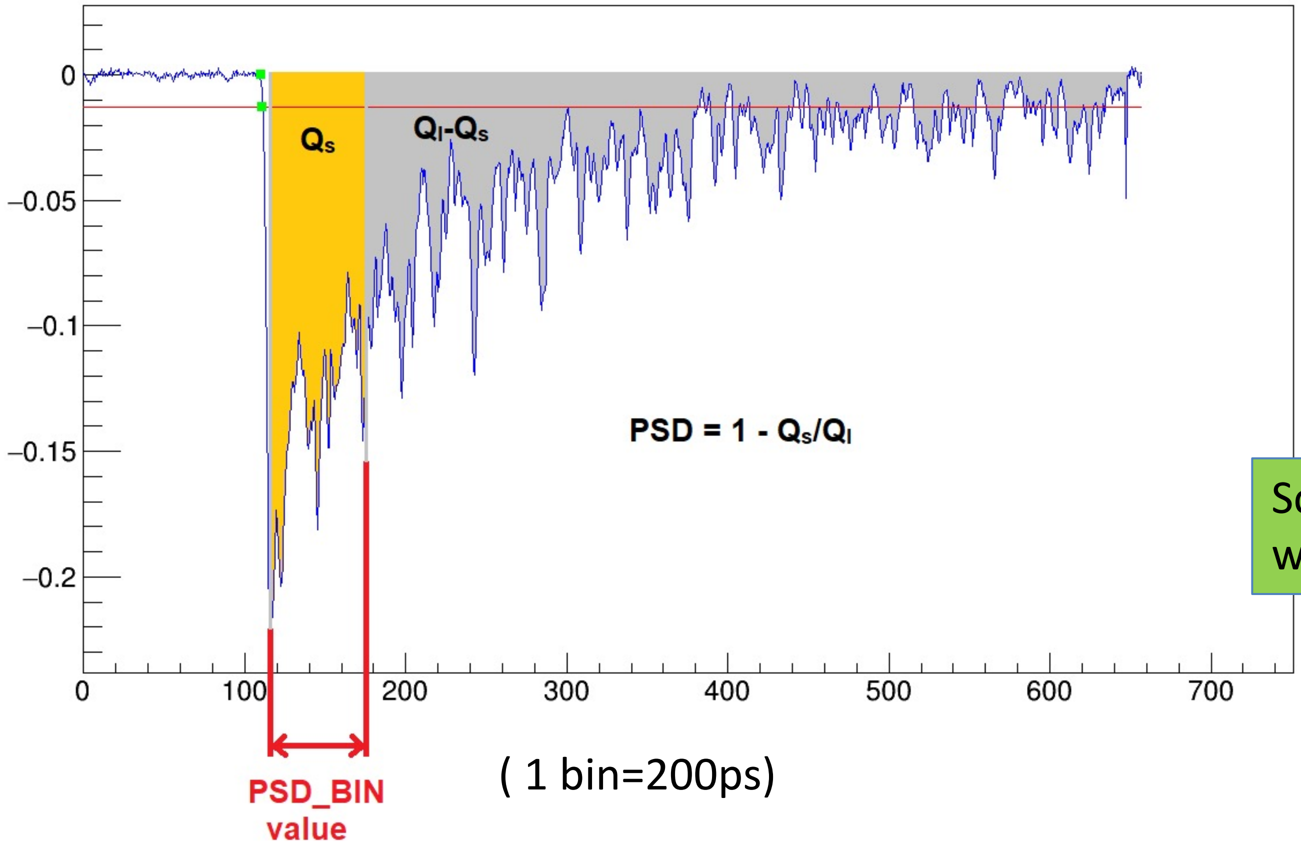


Comparison of enegy distribution and energy deposition from charged particles (protons and alpha-particles) created in GAGG under 200 MeV neutrons.

Both protons and alpha-particles can be utilized for PSD to discriminate fast neutrons

Pulse shape discrimination by digitizing of the signals

A major mechanism of interaction of fast neutrons in GAGG is (n, p), (n, α) reactions on light nuclei. The kinetics of scintillations under α-particles and protons in the initial stage is faster than under the gamma-quanta. This makes it possible to discriminate the signals according to the pulse shape (PSD).



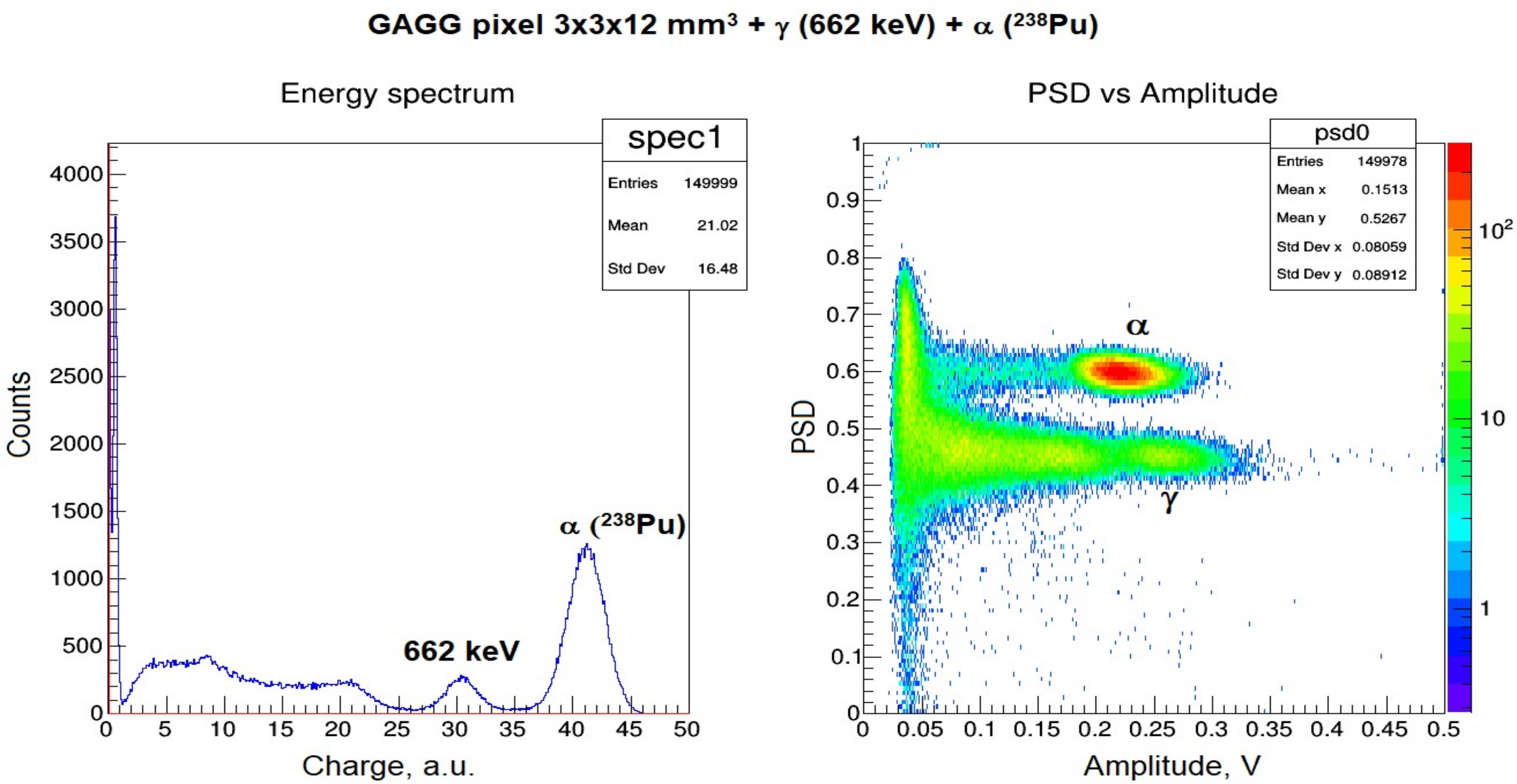
(1 bin=200ps)

$PSD = 1 - Q_s/Q_l$

Scintillation pulse recorded with DRS-4 digitizer (PSI)

Proof of the PSD concept with GAGG

A combined source of α-particles (^{238}Pu) and γ-quanta (^{137}Cs) has been applied to GAGG (3 x 3 x 12 мм) sample.



Conclusions

- **GAGG material has a unique combination of properties, which makes it a candidate to measure neutrons in a wide energy range;**
- **The GAGG pixelated detector with SiPM readout was found to be suitable to detect fast neutrons;**
- **GAGG pixelated detector matrix provides capabilities for more detailed analysis and background discrimination;**
- **Pulse shape analysis can be implemented to discriminate fast neutrons from gamma-quanta background.**

Acknowledgements

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