Activities related to Subtask 3
Deliverable D11.6
Simulations results for various neutron detectors

Extensive simulation studies have been performed using the GEANT4 [S. Agostinelliae et al. NIM A506, 250 (2003)] simulation package to design a low-energy threshold neutron-detector array for different neutron energies, and different geometrical arrangements, as well as to determine the response function of the array.

Physics processes describe how particles interact with material. In GEANT4, these processes are defined in the PhysicsList.cc program. GEANT4 provides examples, where one can find different routines for preparing a simulation package, how one can define the interactions within the frame of GEANT4. In order to follow the neutron interactions in the scintillator material, we took the PhysicsList from one of the advanced examples, from the underground-physics. In this way, we could use the same physics list for following a gamma-ray or a neutron interaction in the scintillator material.

Elastic and inelastic scattering, neutron capture as well as fission are treated by referring to the GNDL3.13 cross-section data. The simulation package was tested using different neutron data libraries: BROND-2.2, CENDL-31, ENDF-V18, ENDF-VII0, JEFF30, JEFF31, JENDL330 and JENDL-4.0. The results agreed reasonably well.

The detection of neutrons is based on their interaction with the scintillator material. The following processes, by which neutrons interact with the detector material, were taken into account:

- elastic scattering on hydrogen and ^{12}C
- inelastic scattering on ^{12}C
- $^{12}C(n,\alpha)$ and $^{12}C(n,p)$ reactions

The energy deposited by the neutron in the detector volume is converted into light output, depending on the type of the interaction. The electron-equivalent energy (E_{ee}) of the deposited energy for protons and α particles can be calculated using the following empirical expressions:

$$E_{ee} = a_1 * E_p - a_2 * \left[1.0 - exp\left(-a_3 * E_p^{a_4}\right)\right] \qquad 1.a$$

$$E_{ee} = a_1 * E_\alpha - a_2 * \left[1.0 - exp\left(-a_3 * E_\alpha^{a_4}\right)\right] \qquad 1.b,$$

where the electron equivalent energy (E_{ee}) and the proton energy (E_p) 1.a) or alpha energy (E_α) 1.b is in units of MeV.

The values of the parameters a_1 – a_4 have been provided by Cecil et al. (NIM A161(1979)439) for protons and alphas as well. In the case of scattering on C, the electron-equivalent energy is very small. The electron-equivalent energy was calculated using the following relation:

$$E_{ee} = c * EC,$$

where c=0.02 (K. Swoda, D. Schmid NIM A476, 155 (2002)).

For each scattering or nuclear reaction of a neutron within the scintillator, the proper electron-equivalent energy was calculated and stored. The summed electron-equivalent energy of all interactions of the neutron was taken to be the electron-equivalent energy of the scintillator for one neutron event.

This electron-equivalent energy calculation can be used only for NE102 type plastic scintillators, or NE213 type liquid scintillator using the above formula and using the parameter values given by Cecil for liquid scintillators.

The main goal of preparing a simulation package (NeutronDetector) was: to determine the intrinsic detection efficiency of a plastic scintillator, optimizing its shape and the geometrical arrangement of a low-energy threshold neutron detector array, consisting 15 plastic scintillator bars.

The LENA (C. Langer NIM A659, 411 (2011)), and ELENS (L. Stuhl NIM A736, 9 (2014)) was constructed based on the simulations using the NeutronDetector package (A. Algora, M. Csatlos).

In the frame of the R3B and EXL collaborations, the first experiments using the ELENS detector array was performed in 2011 and 2012. Figures 1 and 2 show the setup of these experiments.

Fig. 1. The geometry of the experiment performed in 2011 at GSI.

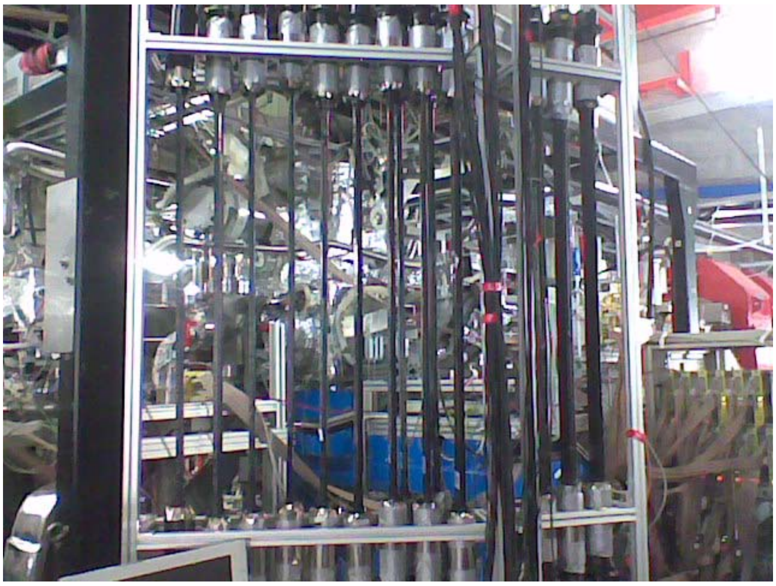

Fig.2. ELENS geometry in the experiment in 2012.

A further experiment was carried out in March, 2014 at RIKEN Laboratory in Japan, where the ELENS detector array was used for detection low-energy neutrons from (*p*,*n*) reaction in inverse kinematics.

The calculated and measured intrinsic efficiencies were compared with each other. It was found that there is a good agreement between the simulated and experimentally-derived intrinsic efficiency as shown in Fig. 3.

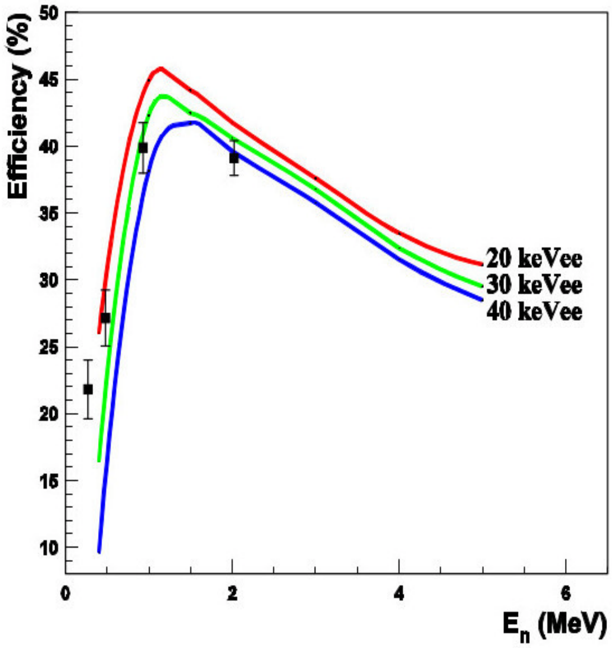

Fig.3. Calculated and measured detection efficiencies.

The geometrical arrangement of the experiment performed at GSI in 2011 was implemented in the simulation package (see Fig. 4).

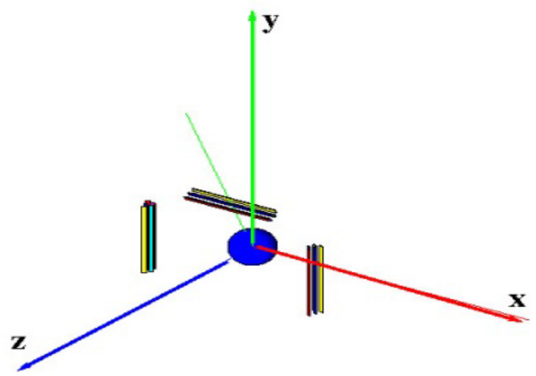

Fig.4 Geometrical arrangement used in the simulation.

The crosstalk between the bars in one module was also studied. One module contains 5 scintillator bars.

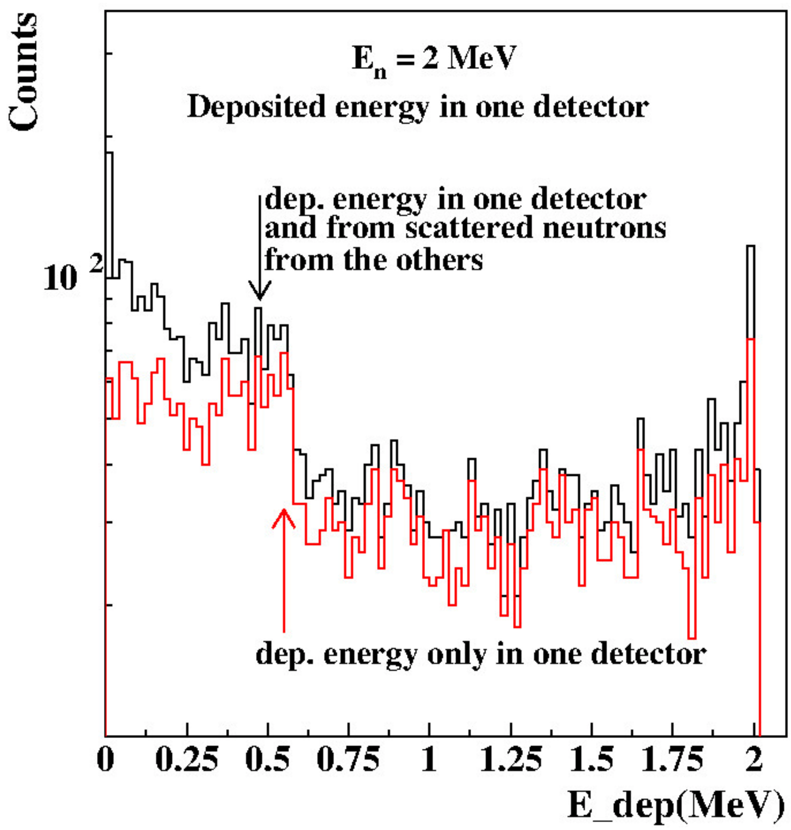

Fig. 5 Study of cross-talk between the bars. Red line indicates the deposited energy in one scintillator bar with the condition that no other detector bars fired. Black line shows the deposited energy in one bar without any condition.

In order to check the response of the array for a continuous neutron spectrum, an event generator for neutrons of a Cf (^{235}U) source was implemented.

From the track and step information, it is possible to deduce the time information. The start time denotes the time, when neutron was released, and one can obtain time information at the end of the event (detection of the particles). The obtained time information was considered as TOF information. The simulated TOF value corresponds to the calculated one from the kinetic energy.

Unfortunately, these scintillators are sensitive not only to neutrons, but they are also sensitive to gamma rays. The gamma-ray sensitivity was studied using an event generator, in which one neutron and one gamma ray are emitted randomly from the same position. The aim was to make an estimation for the detection efficiency of gamma rays, relative to that of the neutrons. From this simulation we obtained that if a neutron and a gamma hit the detector at the same time, the gamma detection efficiency is about 35% of the neutron detection efficiency.

In optimal case, the gamma rays can be distinguished from the neutrons by the TOF spectrum.

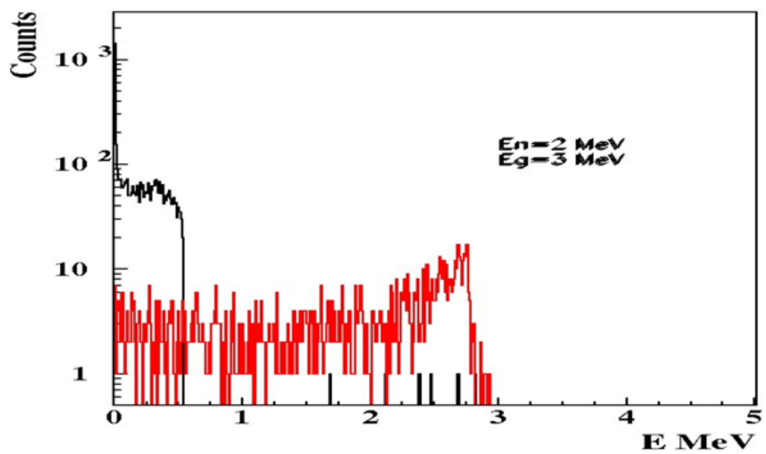

Fig. 6. The simulated response functions for 2 MeV neutrons (black histogram) and for 3 MeV gamma rays (red histogram) as a function of electron-equivalent energy.

A new, NE102A type scintillator bar, 2700x50x50 mm^3 was used to construct a low-energy neutron wall. First the intrinsic efficiency was calculated for one bar (shown in Fig. 7), then for two bars, which are placed alongside closely next to each other, as it is shown in Fig. 6, in order to increase the thickness. The intrinsic efficiency of one scintillator bar is compared to that of the ELENS type scintillator bar in Fig. 7.

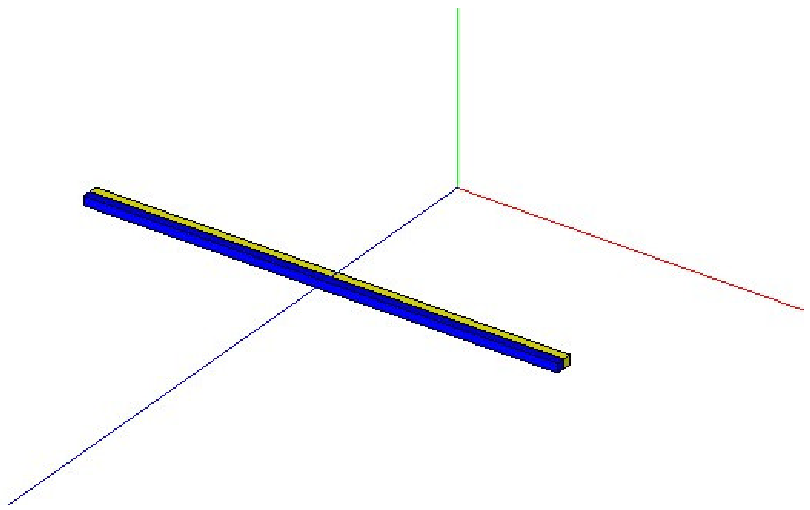

Fig. 6. Placement of two scintillator bars used in the simulation of detector efficiency.

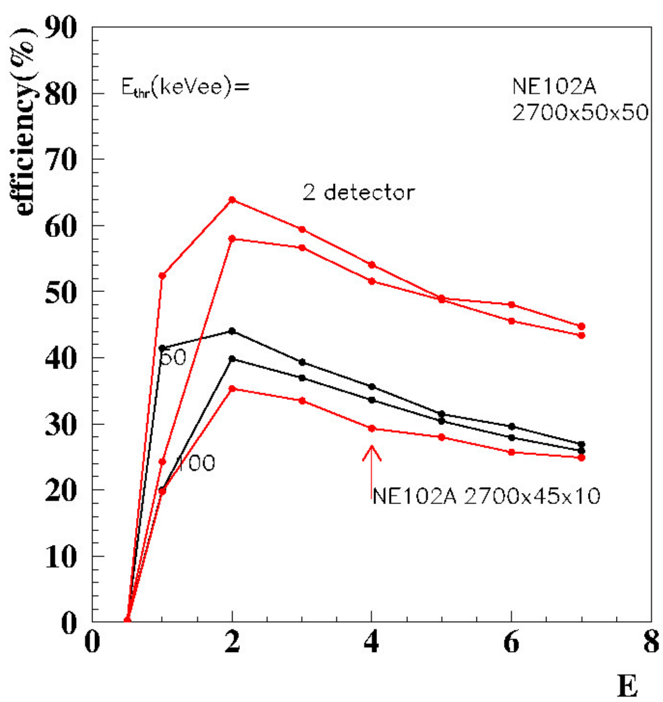

Fig. 7. The black curves indicate the neutron detection efficiency of a NE102A type plastic scintillator bar having a size of 2700x50x50 mm^3 with an energy threshold of 50 keV and 100 keV electron-equivalent energies. The red curve indicated with a red arrow shows the efficiency of the ELENS type scintillator bar. The upper two red curves show the neutron detection efficiency for the two detector cases shown in Fig. 6. The energy threshold given in electron-equivalent energy was also 50 and 100 keV for the upper and lower curves, respectively.

The influence of the wrapping materials (Al and teflon) of the target chamber was also studied.

The simulation package can be used for checking the neutron response of different type detectors. Besides the plastic scintillator, we also started to perform simulations for a detector array using NE213 type liquid scintillators, and 2.5”x2.5” NaI crystal for neutrons having different energies from 0.1 MeV – 10 MeV.

We performed simulations for studying the effect of shielding materials, as paraffin or water, on neutron energy spectra in the NaI crystal as shown in Fig. 8.

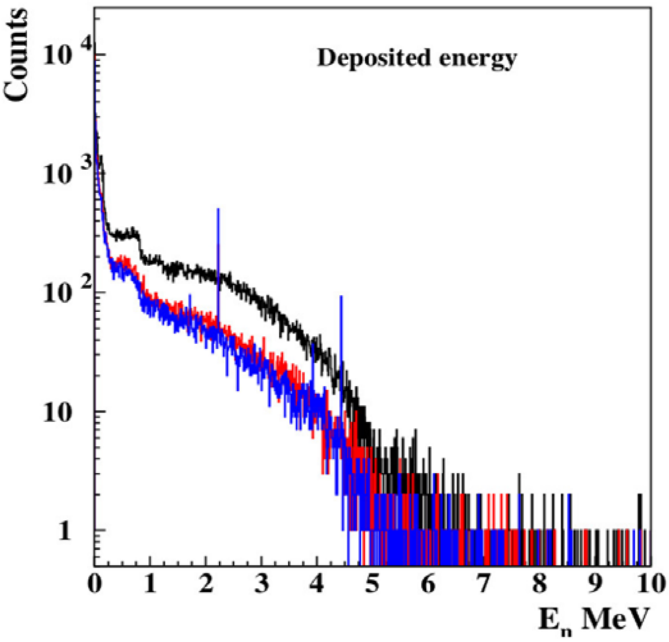

Fig. 8. The black curve shows the deposited energy spectrum in the NaI crystal. The energy of incoming neutrons is 5 MeV. A 10 cm long water tube or 10 cm long paraffin tube was placed as a shielding just in front of the crystal. The red curve indicates the effect of the water; the blue curve shows the effect of the paraffin shield. There is no significant difference between the effect of the paraffin and water shield.