Development of a detector in order to investigate \((n,\gamma)\)-cross sections by ToF method with a very short flight path

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Abstract. The determination of neutron capture cross sections of some radioactive isotopes like \(^{85}\)Kr is very important to improve the knowledge about the s process. Based on its own radioactive decay these isotopes can only be used in small samples inside a TOF facility, which is why the neutron flux of these facilities has to be very high. Unfortunately the neutron flux of the FRANZ setup at Goethe University Frankfurt, which will offer the highest neutron flux in astrophysical energy regions (keV region) \([1]\), is still too low to investigate isotopes like \(^{85}\)Kr. Therefore a new setup called NAUTILUS is under development, which will reduce the flight path from 80 cm to a few centimeter to enhance the angular coverage of the sample and therefore increase the neutron flux by a factor of nearly 100. This implies a higher intensity of the \(\gamma\)-flash energy inside the detector and the neutron induced background. Hence the geometry, the scintillator material and the moderator were optimized by GEANT3 simulations.

1. Motivation

The FRANZ facility will generate the highest neutron flux in the astrophysical energy regions world wide \([2]\). Unfortunately this neutron flux will be still too low to investigate neutron capture cross sections of some interesting isotopes (like \(^{85}\)Kr) \([3]\). Thus, the idea is to increase the neutron flux by reducing the flight path from 80 cm to a few centimeter and in doing so enhance the angular coverage of the sample \([4]\).

Before this new setup can be implement two main challenges have to be managed, which result from the fact that the neutrons will be produced inside the detector. Consequently the \(\gamma\)-flash can interfere with the prompt \(\gamma\)'s from the sample. Also no neutron collimator can be used. This results in a high neutron induced background, which has to fade away as much as possible until the next neutron pulse after 4 \(\mu\)s. This work concentrates on optimizing the geometry, the scintillator and moderator by GEANT3 \(\gamma\)- and neutron simulations \([5]\).

2. Simulations

As the detector has to detect all \(\gamma\)'s of the \((n,\gamma)\)-reaction to identify the isotopes on which the capture occurred a 4\(\pi\) detector is the best choice \([5]\). This detector is segmented in 162 moduls, which effects a good distribution of the \(\gamma\)-flash energy \([6]\). In the simulation the inner radius, the thickness of the crystals and the flightpath of the neutrons were varied. Additionally the effect of different scintillator materials (BaF\(_2\), LaBr\(_3\), LaCl\(_3\)) was tested. The simulations were split into two parts: \(\gamma\)-simulations for efficiency and neutron simulations for background studies.
2.1. Gamma Simulations

In figure 1 all results of simulations of $\gamma$-efficiency are shown. For these simulations $5 \cdot 10^6$ $^{197}$Au($n,\gamma$)-cascades were started in the middle of the detector. The efficiency increases with thicker crystals and bigger inner radius, which is an effect of constant wide gaps (0.1 cm TefAl layer) between the crystals. Figure 1 also demonstrates that $\text{LaBr}_3$ is the best choice regarding the efficiency followed by $\text{BaF}_2$. Single $\gamma$ simulations show that these two materials have nearly the same efficiency up to 2 MeV, but for higher energies the higher Z of Br explains the better property of $\text{LaBr}_3$. For a high $\gamma$-efficiency the detector should have a big inner radius and the crystals should be as thick as possible.

2.2. Neutron Simulations

At the beginning of the neutron simulations the flight path was investigated. This flightpath has to be as short as possible to have a high neutron flux at the sample but also the time between the $\gamma$-flash and (n,$\gamma$)-reaction has to be as long as possible. The best compromise was achieved with a flightpath of 8 cm ($4 \cdot 10^7 \text{n/s/cm}^2$ with 16 ns flight time). At this point $10^7$ neutrons with energy- and momentum distribution correspondigg to a neutron spectrum resulting from the interaction of a 1920 keV proton beam with $^7$Li were started for each simulation [7]. Figure 3 shows that the scintillator material strongly affects the interaction time of the neutron background with the setup. This figure also shows that the backgrounds corresponding events can be as late as the next neutron pulse (green box). Therefore the background events for 15 pulses were accumulated for the background studies (after 4, 8, 12... $\mu$s).

As illustrated in figure 4 the background increases dramatically with thicker crystals. In contrast, bigger inner radius has no influence (except for $\text{LaCl}_3$). The comparison of the materials show that the background of $\text{BaF}_2$ depends strongly on the crystal thickness. As the background shouldn’t be higher than 15 events per $10^5$ neutrons the crystals have to be thinner than 8 cm which effects a too low $\gamma$-efficiency. Hence an neutron absorber has to be used.

2.3. Simulations with absorber

An absorber in form of a hollow sphere was placed into the detector in order to decrease the neutron background [4]. In these simulations two different moderator materials were tested: enriched Lithium hydride ($^6$LiH), which is the best but also a hazardous absorber, and Li-salt ($\text{C}_2\text{H}_2\text{O}_4(\text{Li})_2$) which is used at nTOF setup [8].

The first simulations with both moderators revealed that $\text{BaF}_2$, which was the preferred
scintillator because of its fast light component, provides good results hence these simulations were only done with BaF$_2$. Figure 4 shows that the absorber has a big influence on the background and with it much thicker crystals can be used (12 cm with an 10 cm Li-Salt or 5 cm LiH absorber). Unfortunately the absorber decreases the cascade efficiency as shown in figure 2. Nevertheless the use of an absorber is recommended because the crystals can be choose much thicker. Expectedly LiH is the best choice because much thinner material can be used.

Figure 3. Time depend background for the different scintillators. Green tagged box shows the time interval of the next neutron pulse.

Figure 4. Neutron induced background for different scintillators with and without moderator.

3. Conclusion
The simulations showed that a ToF-facility with an ultra-short flight path is feasible. The best choice for the detector is a 4$\pi$ BaF$_2$ detector with a flight path of 8 cm and a 5 cm thick $^6$LiH absorber. The inner radius has to be as big as possible and the thickness of the crystals should be 12 cm. In this case the neutron flux at the sample will be 4·10$^7$ n s$^{-1}$ cm$^{-2}$ with 16 ns flight time, the cascades efficiency of $^{197}$Au(n,$\gamma$)-cascades will be around 15 % and less then 0.8 background events per neutron pulse is expected.

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