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Design studies for the NeuLAND VETO detector

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Abstract. NeuLAND (New Large-Area Neutron Detector) is the neutron detector for the R³B-experiment (Reactions with Relativistic Radioactive Beams) at FAIR (Facility for Anti-proton and Ion Research). NeuLAND is a fully active detector composed of plastic scintillator bars. Neutrons are detected by the production of charged particles in the scintillators through hadronic scattering. These charged particles are then detected by their scintillation light. Due to the highly granular design of NeuLAND, the primary neutron interaction points can be accurately reconstructed. These reconstructed points contribute to a kinematically complete reconstruction of reactions with relativistic heavy-ion beams in the target, the goal of the R³B-experiment. However, charged particles produced by scattering on other parts of the R³B-setup may provide a significant background. To distinguish the target neutrons from the background, a VETO detector could be placed in front of NeuLAND. This VETO detector is a single plane of thin plastic scintillator bars. It, therefore, provides a high detection efficiency for background particles, but a low detection efficiency for neutrons. For every signal in the VETO, NeuLAND signals can be analyzed with respect to their correlation to the VETO signal and can be eliminated from the further neutron analysis. In this paper, the design of this VETO detector is discussed.

1. Introduction

The R³B-experiment will be located at the high-energy branch of the Super FRagment Separator (Super-FRS) at the FAIR-facility [1]. The general purpose of this experiment is to obtain a kinematically complete reconstruction of nuclear reactions with radioactive beams. These reactions are an important tool for exploring nuclear structure properties far from stability [2]. During an R³B-experiment, a radioactive beam from the Super-FRS impinges on a fixed target. The unreacted beam and the charged reaction products are then deflected by the GSI Large Acceptance Dipole Magnet (GLAD). Different detector systems are located around the dipole magnet to provide a spectrometric analysis of the reaction products. Among these detector systems is the gamma spectrometer CALIFA (CALorimeter for the In Flight detection of γ -rays and light charged pArticles), the ion tracking system (including a time-of-flight wall) and the



NeuLAND neutron detector [2, 3, 4] (see Figure 1). A large vacuum chamber is located downstream of the dipole magnet to reduce the background [3].

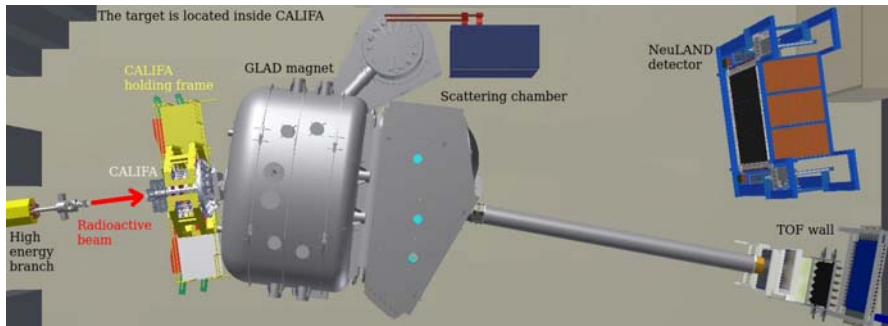


Figure 1:
Overview of the phase 0 R^3B experimental setup in Cave C at GSI. Based on the technical drawings of D. Koerper and used with permission.

The complete NeuLAND detector will be composed of 3000 plastic scintillator bars wrapped with reflective aluminum foil and plastic tape. Each scintillator bar has a dimension of $5\text{ cm} \times 5\text{ cm} \times 250\text{ cm}$ and is read out by two photomultipliers at the far ends. The scintillator bars will be stacked in 60 planes of 50 bars each with alternating horizontal and vertical orientations, providing a fully active neutron detector with an active area of $250\text{ cm} \times 250\text{ cm}$ and a depth of 300 cm [4]. A neutron emitted from the projectile after a reaction in the target can then be detected through hadronic interactions in the scintillator material. The time and space coordinates (called a reconstructed first hit) as well as the kinematic properties of the neutron can be obtained in an offline analysis.

The problem we wish to address concerns the background discrimination in NeuLAND. Charged particles produced in the R^3B -setup through secondary scattering may be detected by NeuLAND. To distinguish the neutrons produced in the target from this background, a so-called VETO detector could be placed in front of NeuLAND. This VETO detector should have a large probability to detect charged particles and a small probability to detect neutrons. For every signal in the VETO, NeuLAND signals can be analyzed with respect to their correlation to the VETO signal and can eventually be eliminated from the further neutron analysis. In this paper, the design of this VETO detector is discussed.

2. Simulation procedure

We used R^3B Root simulations to optimize various parameters for the design of a VETO detector system. R^3B Root is an integrated simulation framework that contains the geometries of all R^3B detectors, specific analysis software for each R^3B detector, and a ROOT control interface [5, 6]. The Monte Carlo simulations in this paper were performed with the Geant3 module of R^3B Root. The physics list has been used successfully for neutron simulations in [4, 7]. After performing Monte Carlo simulations, the detector signals were calculated with the NeuLAND digitizer of R^3B Root. These detector signals were first analyzed with a cluster finding algorithm and then with the neutron tracker software in R^3B Root to obtain the reconstructed first hits (see [4, 6] for more details). See [8] for the source code of the simulations.

3. Detector design

The VETO detector has been designed as a single wall of non-overlapping thin scintillators with a total surface area of $250\text{ cm} \times 250\text{ cm}$, to cover the full frontal active area of NeuLAND. This VETO detector will be placed in front of NeuLAND as shown in Figure 1. The detector design contains three parameters that have to be optimized: the number of scintillators in the wall, the thickness of the scintillators and the distance between the VETO wall and NeuLAND. As a starting point for our optimizations, the geometry of the VETO detector for the NeuLAND demonstrator [9] at the SAMURAI setup [10] was used. The SAMURAI setup is a large-acceptance spectrometer similar to the R^3B -setup (see Figure 1) and is located at RIBF, RIKEN in Tokyo. This VETO contains eight scintillator paddles with a thickness of 1 cm and is placed 32.5 cm in front of the NeuLAND demonstrator.

During the optimization of the distance between the VETO and NeuLAND, the thickness was kept constant at 1 cm and the number of bars was kept constant at eight. The results from this optimization process are shown in Figures 2 and 3 for a neutron, proton or electron beam with 1000 MeV energy and a particle per event. 25000 events were simulated per run. The black curve in Figure 2 shows the percentage of the events where the VETO gave a signal. The red curve shows the part of the events with a VETO signal (black curve) that is only due to backscattering of charged particles from a hadronic interaction in NeuLAND. The gray curve is computed as the difference between the black curve and the red curve. To obtain the blue curve, the timing information of the hits is used: only the events where the VETO hit occurred before the NeuLAND hit were counted. In Figure 3 conditions are as in Figure 2 but for a proton beam or electron beam instead of a neutron beam.

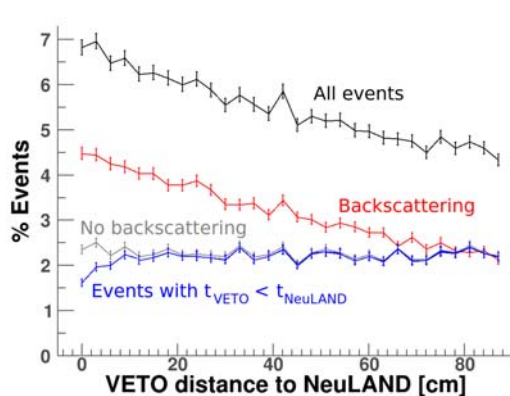


Figure 2: NeuLAND response for 1000 MeV neutrons for different VETO distances.

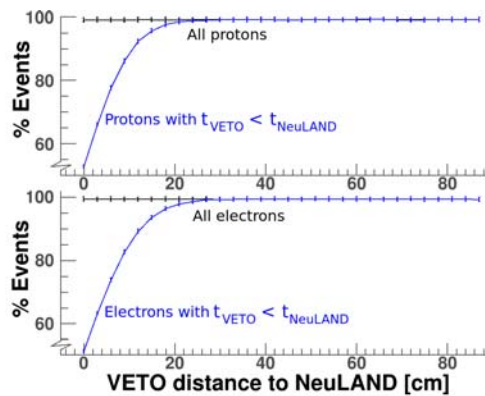


Figure 3: NeuLAND response for 1000 MeV protons (top) and electrons (bottom) for different VETO distances.

Figure 2 shows that the VETO produces a signal for 5% – 7% of all neutrons. We would like to reduce this as much as possible, since one of the design goals of NeuLAND is the efficient detection and reconstruction of multi neutron events up to a multiplicity of four and more [4]. However, as shown in Figure 2, the backscattering signal, which is more than 50% of the total VETO signals, can be efficiently removed from the VETO elimination by using the timing information of the hits (blue curve). For NeuLAND, a time resolution of $\sigma = 150$ ps was used [4]. A typical time resolution (for scintillators) of $\sigma = 300$ ps was assumed for the VETO. On the other hand, Figure 3 shows that this condition allows a significant fraction of the protons and electrons to pass, unless the distance between NeuLAND and the VETO is at least 30 cm. The simulations show no improvement for distances larger than 30 cm for other charged particles. For particle energies less than 1000 MeV, a distinction based on the timing information is always more accurate than for particles with an energy of 1000 MeV. Therefore, simulation of particles with an energy of 1000 MeV suffices in the optimization of the distance. Hence, based on the simulations, the optimal distance between NeuLAND and the VETO is 30 cm.

To optimize the scintillator thickness, we performed simulations with 1000 MeV protons. The number of bars was again kept constant at eight, but the distance was now kept constant at the optimized value of 30 cm. The results are shown in Figure 4 (a threshold of 1 MeV energy deposition was used). The smallest thickness of the VETO scintillators with which all protons can still be detected is 1.1 cm. This provides the VETO with a 100% detection efficiency for all charged particles while the neutron detection efficiency is around 2% (as illustrated in Figure 2). A detection efficiency for charged particles of near to 100% is mandatory in the design of the VETO, because a typical event of an R³B experiment contains multiple charged background particles, which all have to be detected (and eliminated) by the VETO.

Figure 2 also shows the justification of our choice of a single wall of non-overlapping scintillators, since it illustrates that to avoid most of the backscattering, a good time resolution is required for the VETO detector (we used $\sigma = 300$ ps in our simulations). Such time resolutions can only be obtained with scintillators, or with Multi-Resistive Plate Chambers (MRPCs) [11]. However, our timing resolution and

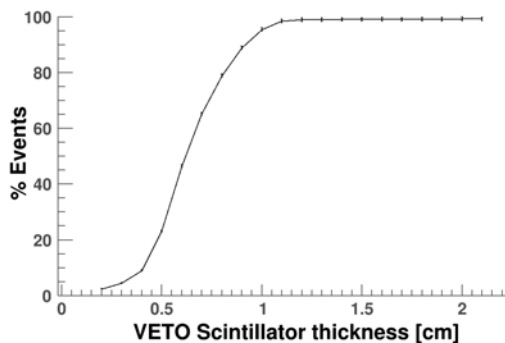


Figure 4: VETO detection efficiency for 1000 MeV protons and for different VETO scintillator thicknesses.

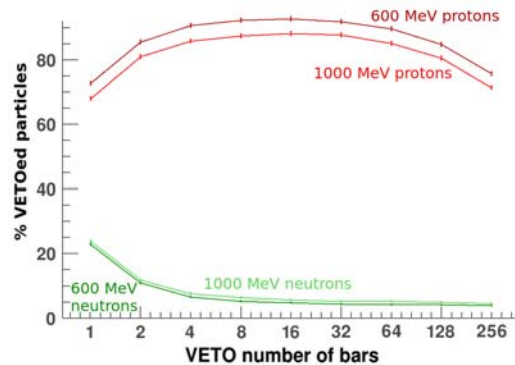


Figure 5: Percentage of VETOed protons and neutrons impinging on NeuLAND in coincidence for different numbers of bars in the VETO.

the requirement that the VETO should detect charged particles with an efficiency of near to 100% would result in a VETO MRPC wall with an areal density that is much bigger than the 1.31 g/cm^2 obtained with a VETO wall consisting of 1.1 cm thick organic BC408 scintillators [4, 12]. This higher areal density results in a larger amount of unfairly eliminated neutrons. The requirement to keep the detector areal density as low as possible is also the reason why the scintillators in the VETO wall should not overlap.

To optimize the number of bars in the VETO, simulations with multiple particles per event and at various beam energies were performed. The distance and thickness parameters were kept constant at their optimized values of 30 cm and 1.1 cm. One reconstructed first hit should then correspond to one incoming particle [4]. This correspondence can be established by minimizing the space and time distances between the reconstructed first hit and the first Monte Carlo interaction point of the incoming track. The proton can then be eliminated by computing straight lines between the reconstructed first hits and the target location. The line that passes closest to the location of the VETO hit is then assumed to correspond to the proton. Figure 5 shows the results of this procedure for a proton and a neutron in coincidence both at 600 MeV or both at 1000 MeV. The simulations show similar behaviour for other energies and for other neutron multiplicities. Therefore, we conclude that the optimal number of scintillator bars in the VETO is 16, although the distribution is rather flat around this number (red and green curves in Figure 5).

4. Efficiency of the VETO wall

To determine the efficiency of the VETO wall under realistic conditions, the entire R^3B -setup has to be included in the simulation to model a realistic background of charged particles. In addition, these simulations require the Geant4 module of R^3B Root to model the nuclear reactions in the target [6]. The Geant4 module contains a physics list which is composed of specific physics builders. These builders were chosen to have a best description of hadronic processes at energies relevant for R^3B -experiments. This physics list was used in our simulations and was benchmarked against another experiment of the R^3B collaboration, S438 [9], to ensure a reasonable agreement with data analysis [13]. Three distinct physics cases were simulated with 10^6 events each: a ^{48}Ca 600 MeV/u-beam on a 1.0 g/cm^2 carbon target, the same beam on a 2.2 g/cm^2 lead target, and a ^{208}Pb 1000 MeV/u-beam on a 500 mg/cm^2 lead target.

The simulations revealed that the neutron background was at least 50% larger than the charged-particle background for all three physics cases. Since the VETO wall is not designed to eliminate neutron signals, an additional method for background reduction was required. Since the neutrons from the target will almost always have an energy close to the beam energy [4], time cuts could be applied to eliminate the neutron background. With proper values for these time cuts, the background of charged particles was reduced by a factor of 5.7 and the neutron background was reduced by a factor of 3.7 for all three physics cases. Only 4% of the neutrons from the target were lost by applying these time cuts [13].

To compare the significance of 4% loss of target neutrons with the significance of the background reduction, the number of successful events was determined. An event was labeled ‘successful’ if reconstructed first hits were obtained for all neutrons from the target, the overall neutron multiplicity was determined correctly, and all background particles were successfully eliminated. Applying the time cuts increased the number of successful events for all three physics cases by 5% – 25% depending on neutron multiplicity [13].

The efficiency of the VETO wall can be quantified in the same way. The VETO wall allowed 46% – 73% of the events contaminated by background particles to be considered as successful events (depending on neutron multiplicity). In addition, around 1% of the neutrons produced in the target were lost due to the use of the VETO wall (on top of the losses due to the time cuts). These numbers were obtained for the physics case of the carbon target. The other two physics cases produced much less neutrons in the target, so that statistically accurate numbers were very hard to obtain. However, the obtained results were consistent with the carbon target case. The 1% loss of target neutrons is almost consistent with Figure 2 if the difference in neutron energy is taken into account. However, due to the reduction of the charged-particle background by the time cuts, the background of charged particles was very low. Hence, the overall effect of using the VETO wall and the time cuts together is a small decrease in the number of successful events with respect to the usage of the time cuts alone [13].

For the simulations mentioned above, it was assumed that the vacuum chamber downstream of the magnet and the beam lines (see Figure 1) were evacuated, a typical situation in the planned experiments. A simulation was also carried out for the case where the scattering chamber and the downstream beam pipe were kept under room conditions (20° C and 1 atm of air pressure). In this case, the applied time cuts successfully eliminated the low-energetic conversion neutrons originating from the chamber walls. The signal-to-noise ratio also increased dramatically by the VETO, making the VETO essential to have if one uses the VETO under these conditions.

5. Conclusion

In conclusion, this work shows that the optimal design of the NeuLAND VETO detector is a single wall of 16 non-overlapping scintillator bars. The total surface of the wall should be 250 cm × 250 cm. The wall should have an active thickness of 1.1 cm, a time resolution of $\sigma \leq 300$ ps, and it should be placed at a distance of 30 cm in front of NeuLAND. The simulation results in this work also lead to the conclusion that the VETO wall does not provide a significant increase in the overall performance, and also cannot improve the signal-to-noise ratio as long as the scattering chamber and the beam pipes are evacuated. However, the VETO detector will provide a much better signal-to-noise ratio for experiments that require atmosphere in the R³B scattering chamber.

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