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Investigation of background reduction techniques for the NeuLAND neutron detector

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ABSTRACT

NeuLAND is the neutron detector used by the R³B collaboration, which is part of the NUSTAR collaboration at the FAIR facility. NeuLAND is used for the detection of fast neutrons in the range of 200 MeV–1000 MeV and is composed of plastic scintillators. Neutrons can undergo hadronic scattering with the scintillator material to produce charged particles, which in turn can be detected by their scintillation light. The high granularity of the detector allows for an accurate reconstruction of the primary interaction points of the neutrons. With these interaction points and with the information from the other detectors in the R³B setup, the reaction at the target can be kinematically reconstructed. This reconstruction is the tool that enables the R³B collaboration to study complex reactions. However, particles produced through reactions of the incoming radioactive beam with other R³B detectors may also enter NeuLAND's active volume and generate a significant background. In this paper, Monte Carlo simulations are utilized to explore possible reduction techniques of this background. In particular, the reduction of the charged-particle component of this background through the use of a VETO wall is explored for the initial setup of the R³B experiment. The list of physics processes considered and their implementation in the simulations are tested against experimental data to ensure that conclusions about the background reduction are meaningful. Extensive simulations show that the use of a VETO wall is, in many situations, not necessary.

1. Introduction

The detector setup of the R³B experiment will be located at the high-energy branch of the Super-FRS at FAIR [1]. The general goal of this experiment is to obtain a kinematically complete reconstruction of nuclear Reactions with Relativistic Radioactive Beams (R³B). Nuclear structure properties, especially those of nuclei far from the valley of stability, can be studied through such reconstructions [2].

The relativistic radioactive beams are produced in the Super-FRS and impinge on a fixed target that is located at the center of the R³B setup. Charged particles produced in the reaction with the target are bent by the large superconducting dipole magnet, GLAD (Gsi Large Dipole magnet) [3]. The tracking system and the vacuum scattering chamber downstream of GLAD serve to detect the ions produced [4]. The protons emerging from the reaction are detected by a separate detection system inside the scattering chamber. The fast neutrons produced in the reaction follow a straight flight path until they reach the

NeuLAND detector [5]. Gamma-rays from the decay of excited nuclei and light-charged particles at large angles are detected by CALIFA (CALorimeter for In-Flight detection of gamma-rays and high energy charged pArticles) [6], which surrounds the target. A silicon strip vertex detector is placed inside CALIFA to measure light charged-particle tracks close to the target [7]. An overview of the R³B setup during the phase 0 experimental campaign [8,9] at GSI is presented in Fig. 1. In this phase, the R³B setup will be used in physics experiments utilizing the present facilities of GSI.

Upon completion, NeuLAND consists of 60 planes of 50 scintillators each [5]. A single scintillator is composed of the material RP408 [11], a hydrocarbon organic scintillation crystal analogue to BC408 [12]. It has dimensions of 5 cm × 5 cm × 250 cm and is read out by a photomultiplier at each end. These dimensions include the aluminium reflective foil (200 μm thick) and plastic tape (500 μm thick) that are wrapped around the scintillators. The planes are stacked behind each other

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Fig. 1. Overview of the phase 0 R³B setup in Cave C at GSI [10], used with permission.

in alternating mutually perpendicular orientations. The full NeuLAND detector will be a Time-Of-Flight spectrometer with a thickness of 3 m and an active area of $2.5 \text{ m} \times 2.5 \text{ m}$. See Fig. 2 for an overview of the NeuLAND detector in the current phase of construction.

NeuLAND is used in the detection of fast neutrons in the range of 200 MeV – 1000 MeV. These neutrons are detected through hadronic scattering within the scintillator material. The knocked-out charged particles can then be detected through their scintillation light. The signals of the photomultiplier tubes are recorded and processed (using both time and calorimetric information) to obtain the time and space coordinates of the initial hadronic interactions of the neutrons with the scintillators [5]. These coordinates then define the position of a so-called *reconstructed first hit*. The kinematic properties of the neutrons can be computed from these reconstructed first hits.

In addition to the detection of neutrons that originate from the reaction at the target (projectile-like neutrons), NeuLAND might also detect particles that are produced by reactions of the beam with other parts of the R³B setup. These particles could provide a significant background to the signals from the projectile-like neutrons. In this paper we have utilized Monte Carlo simulations to explore possible reduction techniques of this background. In particular, we discuss to what extent the charged-particle component of this background can be reduced by placing a VETO wall in front of NeuLAND in the phase 0 setup (see Fig. 1). Ideally, for the Veto wall, the probability to detect charged particles should be small and the probability for neutron interaction should be large, so that the charged-particle component of the background in NeuLAND can be removed by eliminating the coincidence signals with the VETO wall (this procedure is discussed in more detail in the next section). The ideal detector geometry of such a VETO wall has been explored in Ref. [10]. In this work, we explore how effective this VETO wall is for the elimination of the charged-particle background through Monte Carlo simulations of several typical R³B-experiments. The full NeuLAND detector and with the VETO wall, as they were considered in our simulations, are shown in Fig. 3.

The simulation procedure is discussed in Section 2. In Section 3, this procedure is compared to experimental data. Subsequently, in Section 4, the elimination of the neutron component of the background through the use of time cuts is discussed. Finally, in Section 5, the effectiveness of the VETO wall in the elimination of the charged-particle component of the background is discussed. The conclusions are then summarized in Section 6.

Fig. 2. The current state of the construction of the NeuLAND detector. Only 30 of the 60 scintillator planes have been built so far. Since the VETO detector has not been constructed yet, it is not shown here. The VETO detector would be placed in front of NeuLAND as is shown in Fig. 3.

Fig. 3. The full NeuLAND detector together with the VETO wall, as it was considered in our simulations.

2. Simulation procedure

For the present work, all simulations were performed with R3BRoot [13,14]. R3BRoot is an integrated simulation framework with a ROOT [15] user interface and geometry builder and dedicated analysis software programs for each detector system in the R³B setup. The Monte Carlo transport in the simulations was performed with the Geant4 [16] module of R3BRoot.

Two different geometries were used in the simulations. For the comparison to experimental data in Section 3, the geometry of the S438 experiment performed at GSI in April 2014 [17] was implemented in R3BRoot. This geometry was similar to the LAND-R³B setup discussed in Ref. [18], but the neutron detector of the setup was NeuLAND. During the experiment, NeuLAND was located at an angle of 0° to the beam line (the 0° position) and 13 m downstream of the target. This geometry did not include any VETO detector.

For the simulations in Sections 4 and 5, the geometry of phase 0 of the R³B setup (see Fig. 1) was implemented in R3BRoot. In this setup, NeuLAND is located in the 0° position and 14 m downstream of the target. Since the purpose of these simulations is to explore reduction techniques of the background in NeuLAND, a VETO detector of optimal design [10] was placed in this setup in front of NeuLAND. This optimal design is a single wall composed of 16 non-overlapping scintillator bars with a total area of 250 cm × 250 cm. The scintillators are made from the same material, RP408, as the NeuLAND scintillators. They have an active thickness of 1.1 cm. The optimal distance between NeuLAND and the VETO wall is 30 cm. The time uncertainties in the signals of the VETO photomultipliers need to be below $\sigma = 300$ ps and the photomultipliers should have a Constant Fraction Discrimination (CFD) threshold equivalent to an energy deposition in the scintillator between 160 keV and 1 MeV for protons.

The processes considered in the Monte Carlo transport were described by a physics list. This list was composed of the following Geant4 modules [19]: the Geant4 Bertini Cascade module, the IonINCL++ module, the Low Energy QED module, the Gamma-nuclear module and the elastic hadron-collision module. This physics list was used in all simulations of this work. After the Monte Carlo transport, the NeuLAND detector signals were modeled with the NeuLAND digitizer of R3BRoot. The reconstructed first hits were obtained by applying a cluster-finding algorithm on these signals followed by the neutron-tracker algorithm of R3BRoot.

For the elimination of the charged-particle background by the VETO, straight lines from the location of the reaction at the target to the reconstructed first hits in NeuLAND were computed [10]. Subsequently, one reconstructed first hit is eliminated (vetoed) for each VETO signal. The reconstructed first hit that is vetoed, is the one where its line passes closest of all lines (in space and time) to the hit-point of that specific VETO signal. However, that reconstructed first hit is only vetoed if its Time-of-Flight (TOF) is larger than that of the VETO signal. Otherwise, no reconstructed first hit is vetoed, because in this situation the VETO signal comes from backscattering [10]. In order to evaluate whether this method indeed vetoed charged particles, each reconstructed first hit was linked to its specific Monte Carlo track.

At first glance, it may seem confusing that the reconstructed first hit which has its line passing closest to the hit-point of the VETO signal, is also vetoed if that closest passing still holds a large distance (because no threshold was introduced for this distance). However, it is known that the location of the reconstructed first hit does not always accurately represent the location of the corresponding first particle interaction [20]. On the other hand, when a VETO signal is recorded (with a TOF smaller than the reconstructed first hits), it is known for sure that a charged particle has entered NeuLAND, meaning that an attempt has to be made to filter it out. For this reason, it was decided not to introduce a maximum for the distance between the line and the hit-point of the VETO signal, as a distance larger than such a threshold may just be the result of our inability to accurately

determine the position of the first particle interaction. Moreover, with the VETO geometry and time resolution introduced above, there is also a substantial uncertainty in the position of the hit-point of the VETO signal, which further supports our choice against the use of a maximum distance.

3. Comparison between experimental and simulated data

Our simulation procedure was compared to the data from the S438 experiment. The S438 experiment included measurements of three different reactions: a 700 MeV/u ⁵⁸Ni-beam on a 6.8 g/cm² lead target, a 550 MeV/u ⁴⁸Ca-beam on a 0.991 g/cm² carbon target and the same beam on a 2.2 g/cm² lead target.

For the first NeuLAND plane with vertically oriented scintillators, which is preceded by a plane with horizontally oriented scintillators, histograms are displayed in Fig. 4 for all three reactions. The solid lines represent the experimental data. The light-gray histograms show the simulated data. Each histogram bin corresponds to one scintillator in the NeuLAND plane. The CFD threshold of all photomultipliers was set to an equivalent of 1 MeV energy deposition per scintillator for protons.

Figs. 4a–4b display all data for the three reactions used in the S438 experiment. Figs. 4d–4f display the same data, but now with the restriction that the preceding NeuLAND plane gave no signal at all. This condition was implemented to use the preceding NeuLAND plane as a VETO for the rest of NeuLAND. Tracking back the simulated data revealed that almost all counts in Figs. 4d–4f belonged to incoming neutrons, which shows that this condition indeed acts as a rudimentary VETO condition.

Fig. 4 shows that, except for the situation of Fig. 4d (discussed below), a reasonable agreement is obtained for both the situation with and without a rudimentary VETO condition. Since only a single normalization (per reaction) was used to accomplish this, Fig. 4 leads to one very important conclusion: the production ratio of charged and uncharged particles was simulated with reasonable accuracy. This conclusion can be drawn, because almost all simulated particles in Figs. 4d–4f were neutrons, as discussed above, while Figs. 4a–4c show the sum of all particles.

The production ratio of charged and uncharged particles is a crucial aspect in the simulations. The VETO wall eliminates a few percent of the incoming neutrons (due to hadronic interactions in the wall), and is capable of disentangling neutrons from charged particles in events where both particles hit NeuLAND simultaneously [10]. Clearly, the production ratio of charged and uncharged particles determines which of these two effects of the VETO wall is most important and, therefore, how effectively this VETO wall can eliminate charged-particle background.

Unfortunately, Figs. 4a and 4d show that the simulated production ratio of charged and uncharged particles exhibits a large discrepancy with the experimental data (Fig. 4a was used to fit the overall normalization). As the other two reactions are better described by the simulations, we chose to investigate the VETO efficiency with those reactions. However, the beam energy was slightly changed to 600 MeV/u to maintain consistency with the simulated results in Ref. [5].

The VETO efficiency was also investigated with the reaction of a 1000 MeV/u ²⁰⁸Pb-beam on a 0.50 g/cm² lead target. This reaction was chosen as a worst-case scenario in terms of background production because the collision of two Pb-nuclei at these energies results in high particle-multiplicities. All these particles can then undergo secondary reactions with the detector materials. Moreover, the unreacted Pb-beam will also produce a lot of background by undergoing reactions with the R³B detectors.

Hence, three distinct reactions were simulated in Sections 4 and 5: a 600 MeV/u ⁴⁸Ca-beam impinging on a 0.991 g/cm² carbon target (Ca48C), the same beam on a 2.2 g/cm² lead target (Ca48Pb) and a 1000 MeV/u ²⁰⁸Pb-beam on a 0.50 g/cm² lead target (Pb208Pb). From the results displayed in this section, we conclude that the first

Fig. 4. Comparison between experimental (solid line) and simulated (light-gray) data for the S438 experiment. The histograms show the total number of signals recorded in each of the scintillators in the first NeuLAND plane with vertically oriented scintillators. The upper histograms show the data without and the lower histograms show the data with a rudimentary VETO condition from the preceding plane. One normalization factor per reaction was applied to fit the simulated data to the experimental data. The data without rudimentary VETO condition were used to perform the fittings (top histograms) and then the same normalizations were also used for the situation with a rudimentary VETO condition (bottom histograms).

two simulations produced realistic results for the VETO efficiency. The results of the simulation of the Pb208Pb reaction may be less realistic, but can still be used for qualitative predictions about the worst-case scenario.

4. Elimination of the neutron background

In the simulations using the Ca48C reaction, we observed a background originating from neutrons that were not produced at the target (neutron background). This background was at least 50% larger than the charged-particle background [10,21]. An illustration of this neutron background is provided in Fig. 5a. This figure shows the x and z coordinates of the production points of all neutron tracks in the R³B setup for the simulation of the Ca48C reaction. Except for the target (located at the origin), all of these production points give rise to the neutron background.

Fig. 5a shows that the neutron background originates from the entire R³B setup. The Time-Of-Flight wall, the walls of the scattering chamber and its adjacent beampipe, the forward endcap of CALIFA, and the interior walls of GLAD are the main contributors.

Due to its low probability to detect neutrons (which was one of the design goals), the VETO does not have the capability to distinguish projectile-like neutrons from the neutron background. Hence, an additional tool is required to make this distinction. The use of time cuts was proposed: discarding all raw data when the arrival time of a signal is outside of a predefined window [10,21], which can be defined for experiments aiming at the detection of projectile-like neutrons. To eliminate as many background tracks as possible, this window should be as small as possible but should still include all data from the projectile-like neutrons. The identification of the primary interactions of these neutrons in the simulation data provided us with the optimal time window for a beam energy of 600 MeV/u: 52 ns – 72 ns after the reaction at the target. This window allows neutrons with $\beta = 0.65 - 0.90$. It eliminates

Table 1

Comparison of the counted numbers of events for the simulation of the Ca48C reaction with and without the time cuts. The scattering chamber was under vacuum. One million events were simulated.

Use of time cuts:	Mult.	Observed		Analyzed OK		s/n -ratio
		Total	Cont.	Total	Cont.	
No VETO condition and no time cuts	0n	224	0	0	0	0
	1n	50 148	87	2476	0	5%
	2n	8 387	125	2313	0	38%
	3n	7 164	111	1869	0	35%
	4n	6 169	92	1424	0	30%
No VETO condition, but with time cuts	0n	71	0	0	0	0
	1n	13 779	32	3097	0	29%
	2n	9 167	64	2848	0	45%
	3n	8 253	60	2226	0	37%
	4n	5 932	41	1500	0	34%

only 4% of the neutrons of interest, while the neutron background is reduced by a factor of 3.7 and the charged-particle background by a factor of 5.7. The remaining neutron background after applying these time cuts is illustrated in Fig. 5b. When Fig. 5b is compared to Fig. 5a, it is evident that the reduction of the neutron background due to the time cuts is substantial.

The reduction of both the neutron background (observed in Fig. 5b) and of the charged-particle background due to the time cuts can be studied more quantitatively through the number of counts, displayed in Table 1.

The “Mult.”-column in Table 1 denotes the neutron multiplicity, which is equivalent to the number of non-vetoed reconstructed first hits of that event. The “Observed”-column denotes the total number of events in the simulation for which a certain neutron multiplicity was detected. The “Cont.”-Column is the number of events in the simulation that were counted in the “Total”-column and where at least one charged particle track was detected by NeuLAND (meaning

Fig. 5. The x and z coordinates of the production points of all neutron tracks in the simulation for the Ca48C reaction. The y -coordinate is integrated out. Colored versions of these pictures are available online.

that this track triggered at least one scintillator of NeuLAND). The abbreviation “Cont.” stands for “contaminated with charged particle tracks” and this column is shown because we are specifically interested in reduction of the charged-particle component of the background (see Section 5).

The “Analyzed OK”-column is the total number of events in the simulation which were counted in the “Observed”-column, but with the following conditions imposed: (1) each non-vetoed reconstructed first hit belonged to a neutron from the target, (2) the neutron multiplicity matched the total number of incoming neutron tracks from the target, and (3) no uneliminated charged-particle tracks were detected by NeuLAND. Hence, in short, the “Analyzed OK”-column shows the events where all neutrons from the target were correctly detected by NeuLAND.

Since no VETO wall was exploited in the simulations of Table 1, the “Analyzed OK”-“Cont.”-column should contain only zeros. This is, because the “Cont.”-Column contains only events where charged-particle tracks were detected by NeuLAND and the “Analyzed OK”-column is subjected to condition (3). Hence, the “Analyzed OK”-“Cont.”-column can only contain events where all detected charged-particle tracks were correctly eliminated by the VETO wall, which was not used in Table 1. The reason that the “Total”-“Observed”-column adds up to less than the one million events simulated is that for certain events, no trigger signal was generated. These are the events where the beam did not undergo a nuclear reaction of interest within the target.

During an experiment, only the results from the “Observed”-“Total”-column can be measured. Since a reconstructed first hit is nothing more than a (t, x, y, z) -coordinate, the conditions imposed on all of the other columns require information that can only be obtained from the Monte Carlo tracks. However, the “Analyzed OK”-“Total”-column represents the events of interest: the events where all the reconstructed first hits indeed represent all of the projectile-like neutrons. Therefore, the signal-to-noise ratio (s/n -ratio) is defined as the “Analyzed OK”-“Total”-column (signal) divided by the difference between the “Observed”-“Total”-column and the “Analyzed OK”-“Total”-column (noise).

From Table 1, it is clear that the “Analyzed OK”-“Total”-column contains considerably less events than the “Observed”-“Total”-column. We wish to emphasize that more than 87% of the difference between these columns is caused by misidentification of the neutron multiplicity or by linking the reconstructed first hits to the wrong incoming tracks. When the time cuts are applied, this number increases to 92%. From Ref. [5] it is already known that these issues limit the detection of neutrons with NeuLAND and new methods to improve the identification of the neutron multiplicity and of the projectile-like neutron tracks are currently under investigation [9]. However, these improvements are not the purpose of this work. Here, we investigate possible reduction techniques of the background in NeuLAND. Both the signal-to-noise

Table 2

Performance of the VETO wall in the Ca48C simulation. The “No VETO condition, but with time cuts”-section was copied from Table 1 for comparison purposes. The scattering chamber was under vacuum. One million events were simulated.

Use of time cuts:	Mult.	Observed		Analyzed OK		s/n -ratio
		Total	Cont.	Total	Cont.	
No VETO condition, but with time cuts	0n	71	0	0	0	0
	1n	13 779	2091	3097	0	29%
	2n	9 167	483	2848	0	45%
	3n	8 253	552	2226	0	37%
	4n	5 932	490	1500	0	34%
Tracker VETO condition and time cuts	0n	465	256	157	148	51%
	1n	13 939	2167	3126	66	29%
	2n	9 316	542	2850	50	44%
	3n	8 243	520	2176	33	36%
	4n	5 955	512	1463	23	33%
Perfect VETO condition and time cuts	0n	277	206	152	152	122%
	1n	13 841	2153	3187	90	30%
	2n	9 248	564	2944	96	47%
	3n	8 230	529	2297	71	39%
	4n	5 942	500	1549	49	35%

ratio and the absolute number of events in the “Analyzed OK”-“Total”-column show a significant improvement due to the use of the time cuts, especially for lower multiplicities. Therefore, we conclude from both Fig. 5b and Table 1 that time cuts represent a very effective method for background reduction. This is also the reason that these time cuts were employed in all simulations that are discussed in Section 5.

5. VETO efficiency

The efficiency of a VETO detector is evaluated for the Ca48C reaction and the results are displayed in Table 2. The definitions of the columns in Table 2 are the same as for Table 1.

The “No VETO condition, but with time cuts”-section in Table 2 was copied from Table 1 for comparison. The other two sections of Table 2 show the effects of the Tracker VETO condition and of the Perfect VETO condition in addition to the time cuts. The Tracker VETO condition uses the background elimination procedure, vetoing reconstructed first hits if their lines pass closest to the VETO hit points, as outlined in Section 2. The Perfect VETO condition yields the theoretical maximum of what a VETO wall could achieve in the case that only the reconstructed first hits which are linked to charged-particle tracks are vetoed. Obviously, this Perfect VETO condition requires information from the Monte Carlo tracks and can, therefore, never be used during an experiment.

Table 2 shows that the tracker VETO condition saves 46% to 73% of the contaminated events that could be saved according to the perfect VETO condition (See the ratio of the two respective “Analyzed OK”-“Cont.”-columns). The tracker VETO condition also eliminates about

Table 3

Performance of the VETO wall in the Ca48Pb simulation. The scattering chamber was under vacuum. One million events were simulated.

Use of time cuts:	Mult.	Observed		Analyzed OK		<i>s/n</i> -ratio
		Total	Cont.	Total	Cont.	
No VETO condition, but with time cuts	0n	103	3	0	0	0
	1n	11 713	2231	691	0	6%
	2n	1 978	165	384	0	24%
	3n	1 331	127	212	0	19%
	4n	657	71	97	0	17%
Tracker VETO condition and time cuts	0n	418	243	146	127	54%
	1n	11 579	2113	691	9	6%
	2n	1 949	129	379	3	24%
	3n	1 254	84	207	4	20%
	4n	653	66	93	0	17%

Table 4

Performance of the VETO wall in the Pb208Pb simulation. The scattering chamber was under vacuum. 250 000 events were simulated.

Use of time cuts:	Mult.	Observed		Analyzed OK		<i>s/n</i> -ratio
		Total	Cont.	Total	Cont.	
No VETO condition, but with time cuts	0n	47	0	0	0	0
	1n	8139	2755	52	0	1%
	2n	323	167	44	0	16%
	3n	175	63	30	0	21%
	4n	128	27	22	0	21%
Tracker VETO condition and time cuts	0n	226	163	29	28	15%
	1n	8105	2730	53	0	6%
	2n	264	111	41	1	19%
	3n	327	159	29	0	10%
	4n	1103	549	20	0	2%

1% of the projectile-like neutrons. This number of 1% per neutron is obtained from the ratio of the two respective “Analyzed OK”-“Total”-columns after the “Analyzed OK”-“Cont.”-events are subtracted. This 1% (for a beam energy of 600 MeV/u) is consistent with the 2% (for a beam energy of 1000 MeV/u) reported in Ref. [10], when the differences in beam energy are taken into account.

However, due to the lack of charged-particle background (confirmed by identifying the Monte Carlo tracks in the simulation), the absolute number of contaminated events that were saved by the VETO is smaller than the absolute number of non-contaminated events that were lost due to accidental neutron eliminations [10]. This can be seen from the events in the “Analyzed OK”-“Total”-column. When the tracker VETO condition is applied, a small increase in this number of -events is observed for 1n events. For 2n events, this number is about the same, and for the other multiplicities, the overall effect of a VETO is a decrease in his number of events. When the Tracker VETO condition is applied, also the signal-to-noise ratio decreased for all neutron multiplicities (except for 0n, but since NeuLAND is a neutron detector, this increase is not very useful). Hence, from Table 2 we come to the conclusion that a VETO is not useful for the elimination of charged-particle background in the Ca48C reaction.

The results of evaluating the efficiency of the VETO detector for the Ca48Pb and Pb208Pb reactions are displayed in Tables 3 and 4, respectively.

A close inspection of Tables 3 and 4 reveals that the behavior of the VETO wall is roughly the same as in the Ca48C reaction. Similar considerations can be made and the VETO wall does not seem useful for the elimination of the charged-particle background for these reactions either.

However, the situation becomes quite different when the scattering chamber is filled with air. In the simulations up to this point, the scattering chamber (see Fig. 1) was under vacuum. With the scattering chamber filled with 1 atm air at room temperature, the simulation results of the Pb208Pb reaction are presented in Table 5.

The Naive VETO condition in Table 5 is defined such that the entire event is vetoed once a single signal is recorded by the VETO wall.

Table 5

Same as Table 4, but now with the scattering chamber filled with 1 atm air at room temperature. 250 000 events were simulated.

Use of time cuts:	Mult.	Observed		Analyzed OK		<i>s/n</i> -ratio
		Total	Cont.	Total	Cont.	
No VETO condition, but with time cuts	0n	97	1	0	0	0
	1n	24 556	11 308	49	0	0.2%
	2n	6 957	5 992	46	0	0.7%
	3n	3 197	2 754	23	0	0.7%
	4n	1 506	1 239	23	0	1.6%
Tracker VETO condition and time cuts	0n	5 606	4 989	958	890	21%
	1n	24 194	11 383	49	0	0.2%
	2n	4 832	3 911	46	1	1.0%
	3n	2 331	1 780	22	0	1.0%
	4n	3 152	2 035	21	0	0.7%
Naive VETO condition and time cuts	0n	21 434	17 852	4675	3592	28%
	1n	18 207	6 110	47	0	0.3%
	2n	1 891	1 107	44	0	2.4%
	3n	530	176	20	0	3.9%
	4n	261	56	20	0	8.3%

From Table 5, it is clear that both VETO conditions result in only a small drop of the number of “Analyzed OK” events, while the signal-to-noise ratio is significantly improved (except for 4n for the Tracker VETO condition, compared to the No VETO condition). Even with the arguments presented in Section 3, suggesting that this case can be used only for more qualitative predictions, the relative increase is too large to ignore. Therefore, we conclude that the VETO is very useful in the elimination of the charged-particle background for the case presented in Table 5. Moreover, a Naive VETO condition appears to be more effective in this reduction than the tracker VETO condition, as can be seen from the signal-to-noise ratio in Table 5. There are two reasons for this.

The first reason is, that in the situation where charged particles and projectile-like neutrons arrive at NeuLAND in coincidence, the Naive VETO condition would eliminate the projectile-neutrons too. Therefore, the accidental elimination of projectile-like neutrons would be unacceptably high compared to the Tracker VETO condition in the situation where the scattering chamber is evacuated. However, due to the scattering chamber being filled with air, charged particles are slowed down and hit NeuLAND outside the time window. Hence, in this situation the Naive VETO condition will not cause too many accidental eliminations of projectile-like neutrons (see the decrease in “Analyzed OK” events in Table 5 due to the Naive VETO condition).

The second reason is, that major amounts of background are produced by the interaction of the beam, which underwent no reaction in the target, with air. Hence, with the argument from the previous paragraph in mind, it is clear that one does not need a VETO condition to disentangle particles. Instead, one needs a condition that distinguishes between events which are a result of a collision at the target and beam particles which underwent no interaction. This is why the Naive VETO condition performs so well in Table 5.

It is also clear from the signal-to-noise ratio in Table 5 that without the Naive VETO condition (see previous paragraph) it becomes very hard to distinguish the “Analyzed OK” events from the other “Observed” events. With a Naive VETO condition on the other hand, the signal-to-noise ratio is much better and standard analysis techniques (like kinematic cuts and background subtraction) could be employed to get the “Analyzed OK” events out. Hence, we conclude that when the scattering chamber is not under vacuum, a VETO wall could be very effective for the Pb208Pb reaction.

As a final remark of this paper, we would like to emphasize that our conclusions about the VETO wall specifically apply to NeuLAND being in the 0° position. This is a very common situation for R³B experiments [5,8,10]. However, if NeuLAND would be moved to another position where it would no longer be downstream of the magnetic field of GLAD, a VETO wall could become necessary. The

reason for this is, that in such a position charged particles which might be produced by the reaction in the target, will hit NeuLAND in coincidence with the neutrons of interest. When most neutrons of interest are accompanied by charged particles from the target, a VETO wall is very much necessary to disentangle the neutrons from the charged-particles. However, in the 0° position, these charged particles are bent away by the magnetic field of GLAD. Hence, in this situation, the effectiveness of the VETO wall becomes an interplay between accidental neutron eliminations and background reduction, as we have studied in this paper. It was determined that, as long as the scattering chamber is evacuated, the gain from background reduction is less than the accidental neutron elimination, because there simply is not enough background to reduce (see Fig. 5b).

6. Conclusion

From the results of Section 4 we conclude that time cuts may be a very useful tool to reduce both the charged-particle background and the neutron background in NeuLAND. For the Ca^{48}C reaction, this method eliminated only 4% of the neutrons from the target, while the neutron background was reduced by a factor of 3.7 and the charged background by a factor of 5.7. From the results of Section 5 we conclude that for the usual geometry of Fig. 1 and for the reactions investigated, a VETO wall is not a useful device for reduction of the charged-particle background. However, when the scattering chamber of the R^3B setup is not under vacuum, a VETO detector would be very much needed along with the time cuts to keep the signal-to-noise ratio at an acceptable level. In this situation, the most naive and strict VETO condition performs best. Also in the situation where NeuLAND is not in the 0° position downstream of the magnetic field of GLAD, a VETO wall could become necessary.

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