Technical Design Report

Technical Report
for the Design, Construction and Commissioning of
the Beta-Delayed Neutron Detector – BELEN
Abstract

The BEta-deLayEd Neutron (Belen) detector is a 4\pi neutron detector based on $^3$He counters embedded in a polyethylene matrix. This detector will be part of the DESPEC experiment at FAIR and will be used to measure beta-delayed neutron emission probability ($P_n$) together with a beta detector.

This report includes the details about the configuration of the detector for FAIR and the design and construction of a prototype of the neutron detector that has already been used at JYFL and GSI.
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Relative change in the efficiency (measured by two parallel DAQs called analog and digital) when the Cf source is shifted from the center, along the beam axis (left) or along the vertical axis (right) in BELEN. The y-values are ratios of efficiency with respect to the one measured in the center (average of more measurements) for both DAQs. Only statistical errors are take into account. The empty symbols correspond to the case when SIMBA was present in BELEN.

Design for BELEN-48 detector.

Neutron detection MCNPX efficiency for BELEN-48 detector up to 2 MeV.

Neutron detection MCNPX efficiency for BELEN-48 detector up to 5 MeV.

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Detailed view of connections between counters and preamplifiers.

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1 Introduction and overview

The DESPEC (DEcay SPECtrOsCopy)\(^1\) experiment at the Facility for Antiproton Ion Research (FAIR\(^2\)) will perform high resolution and high efficiency spectroscopy with radioactive ion beams. The focus of the experiment will be to address key questions in nuclear structure, reactions and astrophysics for nuclei very far from the valley of stability. The radioactive beams will be delivered by the energy buncher of the Low Energy Branch (LEB)\(^3\) of the Super-FRS\(^4\) (Fragment Separator). These radioactive beams will be formed of secondary reaction products following Coulomb excitation, direct reactions, fragmentation or fission reactions of relativistic radioactive ion beams.

DESPEC is conceived as a modular experiment where different setups can be coupled together in order to study different aspects of decay spectroscopy. The ions of interest will be implanted on an array of a Double Sided Silicon Strip Detector (DSSSD) called AIDA\(^5\) (Advanced Implantation Detector Array) where their $\beta$-decay will be measured. A variety of other detectors will be placed around this DSSSD array according to the experimental needs, such as a compact Ge array, neutron detectors, fast timing BaF\(_2\) detectors, a total absorption spectrometer and equipment for g-factor measurements.

The device described in this report is the BEta-deLayEd Neutron detector (BELEN) that will measure the probability of neutron emission after beta decay ($P_n$), and half-lives of very neutron-rich nuclei.

The $\beta$-delayed neutron emission takes place when a precursor nucleus beta-decays and the resulting daughter-nucleus emits a neutron, see figure 1. This neutron emission is energetically allowed if the excitation energy of the state populated in the beta-decay, $Q_\beta$, is larger than the neutron separation energy of the daughter-nucleus, $B_n$.

![Figure 1: Decay scheme of a beta-delayed neutron emission.](image)

The study of beta-delayed neutron emission probabilities, $P_n$, is of interest for different fields, such as nuclear structure, nuclear astrophysics and nuclear technology applications. In the astrophysical r-process, the delayed neutron emission influences the r-process progenitor abundances along the decay of neutron-rich nuclei back to stability during stellar nucleosynthesis.

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\(^1\)HISPEC/DESPEC technical design report

\(^2\)FAIR: Facility for Antiproton Ion Research

\(^3\)LEB technical design report

\(^4\)SuperFRS technical design report

\(^5\)AIDA:
and constitutes a source of late neutrons during freeze-out [1, 2]. Improved experimental data from delayed neutron emission represents an important input for theoretical calculations since properties of nuclei on the expected r-process path can only be predicted by extrapolation on the basis of systematics of experimental $T_{1/2}$ and $P_n$ values.

Furthermore, in nuclear structure, beta-delayed neutron emission constitutes an important probe for the structure of neutron-rich nuclei far away from the valley of stability where other measurements are not yet possible [4, 6, 7]. The probability of neutron emission after beta-decay, $P_n$, carries information on the beta-strength above the neutron separation energy, $B_n$. The technological interest of this type of study is related to nuclear power generation. In nuclear fission beta-delayed neutron emission plays an essential role in safely controlling the sustainability of the fission reaction. Research of such nuclei is, therefore, fundamental for the design of safer and more efficient nuclear reactors. In this sense in year 2011, the IAEA (International Atomic Energy Agency) boosted the creation of a Coordinated Research Project (CRP) on $\beta$-delayed neutron emission evaluation [3] to study the need for Compilation and Evaluation of $\beta$-delayed Neutron Probabilities, define $\beta$-delayed neutron precursors as "standards" for the purpose of data evaluation and measurements, and elaborate a list of priorities for evaluation and new experiments for reactor physics and nuclear structure/astrophysics.

Despite the high interest in accurate $P_n$ data and the amount of experimental data available nowadays, its quality is not sufficient for the various scientific and technical applications and it is necessary to perform new high precision measurements. The new FAIR facility will contribute to this quest for accurate data by granting access to very exotic nuclei that could not be explored in the past.

2 Physics requirements for the system

The BEta-deLayEd Neutron (BELEN) detector has been designed for FAIR as part of the DESPEC setup. The purpose of this detector is the measurement of neutron emission probabilities after beta decay. The BELEN neutron detector will be used jointly with an implantation setup called AIDA that will be placed inside the beam hole. The beam of ions will be implanted on the DSSSD where they will beta-decay and the subsequent neutrons will be detected by BELEN.

The neutron detector consists of a block of polyethylene with a beam hole in the center and three concentric rings of cylindrical $^3\text{He}$ proportional gas counters able to detect neutrons through the following reaction in the $^3\text{He}$ gas:

$$^3\text{He} + n \rightarrow ^1\text{H} + ^3\text{H} + 765 \text{ keV}$$

The placement of the neutron counters has been carefully chosen via Monte Carlo simulations with the aim of achieving the maximum neutron detection efficiency while keeping this efficiency as constant as possible along the expected energy range for the neutrons (from 100 keV to 5 MeV). The need for a constant efficiency comes from the fact that it is not possible to retrieve the initial energy of the neutron with the reaction $n + ^3\text{He}$. The information provided by this detector will be the number of neutrons detected without any energy information. A very important feature of the $^3\text{He}$ gas is the fact that it has no lower detection threshold for the neutron energy. Furthermore it has negligible sensitivity to gamma-rays, which takes away the concern about neutron-gamma discrimination.

The energy released in the reaction will be deposited in the gas and collected by the electronic chain. In the cases that the reaction takes place close to the walls of the detector, one of the
particles could deposit part or all its energy in the wall and therefore the collected energy will be reduced. This wall effect spreads the expected energy of the neutron detection reaction from 191 keV to 765 keV, as it can be seen in figure 2.

The polyethylene matrix plays a major role in the neutron detector; it reduces the neutron energy due to the collisions with the hydrogen atoms in the polyethylene. The energy moderation of the neutrons is necessary since the cross section for the detection reaction increases as the energy of the neutron decreases, as shown in Fig. 3.

3 Summary of Monte Carlo simulations

3.1 Layout of the neutron detector

The design of the detector has been calculated by Monte Carlo simulations with the MCNPX 2.5.0 code at ARGOS cluster at UPC-SEN (Universitat Politècnica de Catalunya - Secció d’Enginyeria Nuclear), Barcelona, Spain. The main objective of the simulations was to achieve the maximum neutron detection efficiency while keeping a flat efficiency along the expected energy range for the neutrons (from 100 keV to 5 MeV). The flat efficiency is needed by the fact that the information on the energy of the detected neutron is lost due to the moderation process along the polyethylene. A large simulation process has led to the final decision on the design of the final detector. Different aspects about the neutron moderation in the polyethylene have been included, as well as, the optimal distribution of the counters within the polyethylene matrix, and the $^3$He gas pressure of the counters and their length. Details of the simulations are presented in the sections below.
3.2 Neutron moderation in polyethylene

The first step of the simulations was the neutron moderation effect in a polyethylene matrix in order to determine where the rings of $^3$He counters should be placed. Different simulations were performed considering a polyethylene block of dimensions $4 \times 4 \times 4$ m with an 8 cm radius beam hole, and assuming monoenergetic neutrons emitted isotropically from the centre of the beam hole. The results are shown in figure 4, where the corresponding figures to the projection of the spread of the neutrons through the polyethylene block are shown. The rows present different initial neutron energies and the columns present the time elapsed from the moment of the neutron emission. The colour shades indicate the density of neutrons with an energy below $10^{-7}$ MeV, red showing the highest density ($>200$ neutrons/cm$^2$) and light blue the lowest ($<20$ neutrons/cm$^2$). As can be seen in the figures, the higher the initial energy of the neutron, the longer time the neutron requires to be moderated inside the polyethylene matrix and the further it scatters away from the center of the detector. From this figure it was concluded that the maximum spread away from the origin of a 10 MeV-neutron in the polyethylene block was around 30 cm whereas a 1 eV-neutron could only spread about 15 cm. This confirmed that lower energy neutrons would be mainly detected in the ring with the detectors closest to the beam hole, whereas higher energy neutrons would be detected in the rings further away.

3.3 $^3$He pressure analysis

Monte Carlo simulations have been performed using GEANT4 to determine the optimum gas pressure and counter length. The setup of these simulations is shown in figure 5. A single $^3$He counter, including a narrow air hole and the steel wall (figure 5b), is embedded in a $1 \times 1 \times 1$ m$^3$ polyethylene block (figure 5a). This block has a cylindrical air hole in the center where the neutron point source is located.

The dimensions of the counter are all fixed except its effective gas length. This length
Figure 4: Summary table of neutron flux in the polyethylene block for different source energies and neutron propagation times. Front view. Dimensions of x and y-scale are in cm. The colour shades indicate the density of neutrons with an energy below $10^{-7}$ MeV, red shows the highest density (>200 neutrons/cm$^2$) and light blue the lowest (<20 neutrons/cm$^2$).
(a) General view  
(b) Detailed view

Figure 5: Sketch of the simulation. The gas radius is $R_g = 12.19 \text{ mm}$; the external tube radius is $R_w = 12.7 \text{ mm}$; the hole radius where the tube is inserted is $R_h = 12.78 \text{ mm}$; $D$ is the distance from tube axis to the beam hole axis; $L$ is the tube length. The beam hole diameter is 110 mm (represented in the figure 5a as $L$) in conjunction with the moderation distance ($D$) and the gas pressure are the key factors to find the configuration that optimizes the neutron detection.

It is significantly important to estimate the optimal gas pressure in order to avoid an overrun cost, since the cost of the $^3\text{He}$ gas increases linearly with the quantity, and a higher pressure directly means a higher density. A simulation with the previous setup (figure 5) has been carried out changing the gas pressure from 2 atm to 20 atm for 9 different initial neutrons energies (from $10^{-4}$ to 10 MeV). It is important to specify that the moderation length (variable $D$ in the figure 5a) is defined by the 1 MeV energy neutrons at 65 mm. At the same time, the effective length of the counter (variable $L$) is set at 600 mm. The results obtained are presented in figure 6a.

Figure 6: Variable pressure results.

From figure 6a it is possibly to assume that the efficiency has the same tendency for all initial energies. Thus, the energy average efficiency has been calculated to find the optimal pressure.
Observing figure 6b, which represents the average efficiency for all the energy range, a pressure between 8 and 10 atm is considered as the optimal pressure for the $^3$He gas inside the detector counters due to the fact that above this point the increase of the detection efficiency is lower than the increase of the $^3$He cost.

### 3.4 Counter length analysis

In order to determine the optimum effective length of gas counters different Geant4 simulations have been done ranging the counter length from 300 to 900 mm and the distance from 90 to 180 mm ($L$ and $D$, figure 5a) for the whole energy spectrum. The gas pressure has been set at 8 atm. The results of these simulations are plotted in figure 7. It is easy to extract from there that the closer to the center the tube is located, the higher is the efficiency. At the same time, increasing the length of the tube, the efficiency enhances too. However, the scale of the plot does not permit to see whether the increase of length improves the neutron detection likewise for the different moderation distances.

![Figure 7: Variable length and distance absolute results.](image)

Therefore, two new output magnitudes have been created to be able to find differences within the coupling of $L$ and $D$ parameters. One magnitude, the Relative efficiency, is calculated dividing each value by the first length value for each distance. Hence, it will be possible to see the relative differences as the tube length increases (figure 8a). The second magnitude represents the Change of efficiency, calculated from the derivative curve of the Relative efficiency for the four distances, which is plotted in figure 8b.

It can be seen that the location of the tube has a great influence on the detection efficiency regardless of tube length (figure 7). On the contrary, the relative efficiency does not increase in the same proportion while increasing the tube length (8a); limiting the tube length is important as regard to the cost.

Finally, taking into account the different increments of length (figure 8b), it is easy to see that an increment of length from 400 to 500 mm contributes with an efficiency gain higher than
a 6%, while the next increments lead to an efficiency gain below the 3%. An effective tube length between 500 mm and 600 mm will be considered as the optimum.

4 Previous tests and prototypes

4.1 Preliminary tests with a $^{252}$Cf source

Two tests were performed at the UPC laboratory in order to validate the MCNPX simulations and the proper operation of the counters. The first test checked the response of the counters separately while the second test verified the use of a full detector prototype.

4.1.1 First preliminary test

A preliminary test of the $^3$He counters and electronics was performed to check all the system for the design of the BELEN detector. The test was done in the UPC laboratory in Barcelona and reproduced with MCNPX in order to compare the results. The design of this experiment was conceived regarding the following goals:

- To check the functionality of the counters.
- To determine the influence of the signal cable length between the counter and pre-amplifier.
- To check the influence of the electronics warming.
- To identify the spectrum of the neutron detection in these counters.

During the test 22 counters at 20 atm (see characteristics in table 1) were tested separately in the setup shown in figure 9. Those counters were purchased to implement the first design of BELEN. The experience with the first experiments and the improvements in the simulations suggested to increase the amount of counters. In order to assume the cost of the new counters, and according to the effect of the pressure in the efficiency results (section 3.3), the optimal solution was to decrease the $^3$He gas pressure to 8-10 atm. The neutron source used during the
The primary aim of the measurements was to check the response of all counters and electronics. These measurements were made during 20000 seconds for each counter. The cable length between the counter and preamplifier was 5 cm. Counters were connected one by one to the same channel of the preamplifier. The typical response function is presented on figure 10a.

The next measurement was to check the influence of the cable length between the counter and pre-amplifier. The cable lengths tested were 5 cm, 50 cm, 75 cm and 100 cm. The test was made with the same counter and the response function can be seen on figure 10b.

It can be extracted that there are no significant differences between the use of different cable lengths. Therefore, the cable length chosen is 75 cm due to geometrical constraints of the detector.

In order to check the influence of warming up of the electronics two tests were performed: a measurement just taking the data after switching on the electronics ("cold start") and another measurement 5 hours after switching it on ("hot start"). The difference in the number of counts

Table 1: Summary of the main characteristics of the proportional counters used at the tests.

<table>
<thead>
<tr>
<th>Counter</th>
<th>Gas</th>
<th>Physical length (mm)</th>
<th>Effective length (mm)</th>
<th>Physical diameter (mm)</th>
<th>Effective diameter (mm)</th>
<th>Gas pressure (atm)</th>
<th>Cathode material</th>
</tr>
</thead>
<tbody>
<tr>
<td>2527 LND inc</td>
<td>He</td>
<td>686.84</td>
<td>604.8</td>
<td>25.4</td>
<td>24.38</td>
<td>20</td>
<td>Stainless Steel</td>
</tr>
</tbody>
</table>

Figure 9: Experimental setup for simple test [12].
(a) Response function for a single counter [12].  

(b) Response for different cable lengths [12].

Figure 10: Single counter response function.
obtained between hot and cold start was about 1% [12]. Hence, as the difference gives about 1% of uncertainty, to make the measurement quicker, it is possible to start collecting data after connecting the electronics and it is not necessary to wait for the warming up of the electronics after each connection.

Finally, MCNPX simulations were done to obtain the efficiency of the setup and compare this data with the experimental test. The only simplification was related to the neutron energy spectrum since the neutron energy was set to 2.2 MeV. Simulation results are presented in table 2 where it can be seen that there is a good agreement between simulations and experimental data for $^3$He counters.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental data</td>
<td>2.26 ± 0.09</td>
</tr>
<tr>
<td>MCNPX data</td>
<td>2.41 ± 0.07</td>
</tr>
</tbody>
</table>

Table 2: Experimental and simulated (MCNPX) detection efficiency of the counters [12].

### 4.1.2 Full detector prototype test

In order to validate the simulation data and to check the electronic chain a full test of the system was performed at the UPC laboratory in July 2009 using the same $^{252}$Cf neutron source as in the previous test. The aim of this test was to measure the experimental efficiency of a full detector prototype and to compare it with simulations.

The prototype tested was BELEN-20, which consisted in 20 proportional counters (see characteristics in table 1). These proportional counters were assembled inside the polyethylene matrix with dimensions 50x50x80 cm$^3$ in two rings. The first ring contained 8 counters and the second ring 12 counters. The neutron source was placed in the central hole of the polyethylene matrix. This structure was chosen according to the previous MCNPX simulation in order to have the efficiency curve as flat as possible for a wide range of initial neutron energy. A NaI(Tl) detector was inserted inside the central hole as close as possible to the neutron source to validate the proper operation of the electronics and data acquisition system. The full setup can be observed in figure 11. The polyethylene shielding was not placed around the detector due to its large weight and the limitation on floor resistance of the building. Due the low neutron background at our laboratory, the lack of the shielding does not influence the results of the experiment.

Some neutron spectra obtained can be observed in figure 12. There is the first wall effect which corresponds to the energy of 191 keV and the second wall effect corresponding to 574 keV, which is overlapped to the main peak that corresponds to the full energy deposition at 765 keV.

The efficiency measured in this test has a value of $(29±4)\%$ for the $^{252}$Cf average neutron energy (2.3 MeV). This value is represented as a red triangle in figure 13 in conjunction with the efficiency of the neutron detection obtained by MC simulations for neutron energies up to 6 MeV. Despite the fact that the uncertainty of the experimental efficiency is rather large (the contribution to the uncertainty comes mostly from the uncertainty of the activity of the source and the contribution to the uncertainty coming from the count rate is less significant), it is possible to confirm that the efficiency measured in this experiment is in accordance with the MC simulations.
Figure 11: BELEN-20 prototype during the test at UPC (2009)[12].

Figure 12: Neutron energy spectrum for 4 different counters [12]. Above from inner ring, bottom from outer rings.
Figure 13: Efficiency of the neutron detection vs MC simulation calculated [12].
4.2 Previous prototypes

Three different prototypes of the BELEN detector have been designed, constructed and tested until 2013. The first two prototypes used 20 counters (BELEN-20), while the last prototype, named BELEN-30, was composed by 30 counters. The BELEN-20 detectors were tested in two experiments at JYFL in 2009 and 2010. The BELEN-30 was tested at GSI in 2011.

4.2.1 BELEN-20 at IGISOL Trap in JYFL (2009)

In November 2009 the BELEN-20 prototype was validated at JYFL using the pure beam delivered by the Penning trap JYFLTRAP. This prototype consisted of 20 counters distributed in two rings around the beam hole. The details of this configuration are explained in table 3 while a layout of the prototype is shown in figure 14. The counters are embedded in a 50 cm x 50 cm x 80 cm polyethylene matrix and surrounded with a 20 cm thick shield on each side, which increases the matrix dimensions to 90 cm x 90 cm x 80 cm [13].

<table>
<thead>
<tr>
<th>Units in mm</th>
<th>Central hole</th>
<th>Rings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inner</td>
</tr>
<tr>
<td>Diameter</td>
<td>110</td>
<td>220</td>
</tr>
<tr>
<td>Counter holes diameter</td>
<td>–</td>
<td>27.5</td>
</tr>
<tr>
<td>Number of $^3$He counters at 20 atm</td>
<td>–</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 3: Configuration details of the BELEN-20 prototype.

The efficiency of the BELEN-20 prototype according to Monte Carlo simulations with MCNPX is shown in figure 15. It is close to 30% from 1 keV to 1 MeV, and it only decreases around a 5% up to 5 MeV.

At JYFLTRAP, radioactive species were produced by deuteron ($E_d = 30$ MeV) inducing fission on an uranium target. The IGISOL isotope separator was used for isobaric separation of the beam which was then introduced in the Penning trap acting as a very high resolution mass
separator, allowing in fact isotopic separation. The isotopically pure beams extracted from the trap were directed inside a vacuum tube inserted to the centre of the detector, where they were implanted on a movable tape. Two collimators were used to define the implantation position. At the end of the vacuum tube a Si detector (0.9 mm thick, 25.2 mm diameter) was placed for the detection of beta-particles closely behind the implantation position (distance 3 mm) also in vacuum. The instrumentation was complemented with an 80% efficiency HPGe detector for the detection of gamma-rays, situated inside the central hole of the counter at a distance of 9 cm from the tape.

Measurements were performed for neutron rich isotopes with well known $P_n$ values and with a $^{252}$Cf source were used to obtain the counter detection efficiency and verify the Monte Carlo simulations.

Figure 16 shows the detection setup used at JYFL in the JYFLTRAP line including a HPGe detector that was used to detect the gamma rays in coincidence with the beta decay and the neutron emission.

4.2.2 BELEN-20 updated at IGISOL Trap in JYFL (2010)

An update of the BELEN-20 prototype was designed, built and tested in June 2010. The new BELEN-20 was used also at JYFL in the JYFLTRAP line and in the same conditions as the previous detector. However, in this case the nuclei of interest set the maximum neutron energy around 1 and 2 MeV. This fact facilitated to obtain a greater detection efficiency approaching the counters to the beam hole since less moderation length was required for the high energy neutrons. The new configuration is detailed in table 4. The tubes are embedded in a high density polyethylene matrix, with overall dimensions 90 cm x 90 cm x 80 cm, which acts both as neutron moderator and neutron background shielding [14] as in 2009 prototype.

Monte Carlo simulations were performed to obtain the detection efficiency, in figure 17. This configuration was optimized for an energy range up to 2 MeV, and therefore the detection efficiency have a value between 40% and 50% up to 2 MeV, and it decreases to a 30% at 5 MeV.
Table 4: Configuration details of the updated BELEN-20 prototype. The central block with a diameter of 130 mm while all the rest of 110 mm.

<table>
<thead>
<tr>
<th>Units in mm</th>
<th>Central hole</th>
<th>Rings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inner</td>
</tr>
<tr>
<td>Diameter</td>
<td>110-130</td>
<td>190</td>
</tr>
<tr>
<td>Holes diameter</td>
<td>–</td>
<td>27.5</td>
</tr>
<tr>
<td>Number of $^3$He counters at 20 atm</td>
<td>–</td>
<td>8</td>
</tr>
</tbody>
</table>
It is important to note that the center of the matrix has a hole (10 diameter) along the beam line. The total length of this hole is 130 cm. The MC simulations determined that a higher detection efficiency was obtained using that setup [14].

Figure 17: MCNPX efficiency for the updated BELEN-20 prototype [14].

4.2.3 BELEN-30 at GSI (2011)

In August 2011 a new BELEN prototype was validated at GSI laboratory in an experiment using the FRS (Fragment Separator) facility [15]. The new prototype, called BELEN-30, consists of 30 $^3$He counters distributed in two rings. The inner ring, with a diameter of 29 cm, consists of 10 counters of 10 atm. The outer ring is formed by 20 counters of 20 atm at 37 cm (details in table 5 and figure 18). The dimensions of the polyethylene matrix were 90 x 90 x 80 cm$^3$ including a 20 cm shielding against room background and thus a total weight of 600 kg. An additional polyethylene wall with another 30 cm shielding was installed before the setup (collimator) in order to reduce the in-beam neutrons.

<table>
<thead>
<tr>
<th>Units in mm</th>
<th>Central hole</th>
<th>Rings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inner</td>
</tr>
<tr>
<td>Diameter</td>
<td>230</td>
<td>290</td>
</tr>
<tr>
<td>Holes diameter</td>
<td>–</td>
<td>27.5</td>
</tr>
<tr>
<td>Number of $^3$He counters at 10 atm</td>
<td>–</td>
<td>10</td>
</tr>
<tr>
<td>Number of $^3$He counters at 20 atm</td>
<td>–</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5: Configuration details of the BELEN-30 prototype.

Using the linear accelerator UNI-LAC coupled to the SIS-18 synchrotron it was possible to produce a $^{238}$U beam with an energy of 1 GeV per nucleon. This beam impinged onto a
beryllium production target and nuclei of interest were selected using the FRagment Separator FRS via the $B_\rho - \Delta E - B_\rho$ method.

The detection system comprised the BELEN-30 prototype in conjunction with the Silicon Implantation Beta Absorber (SIMBA) detector [5]. The SIMBA detector is a multilayer silicon detector used as implantation detector to detect implants and beta decays in this setup. The SIMBA version used in this experiment is an updated version adapted to BELEN from the one used in previous measurements [16]. A detailed view of the SIMBA detector placed inside BELEN is shown in figure 19.

According to MCNPX simulations, this BELEN prototype shows an approximately constant efficiency of 40% from thermal up to 1 MeV neutrons (figure 20). The detection efficiency has been measured by placing a double encapsulated Cf (mostly $^{252}$Cf) source in the center of BELEN and by summing the neutron events in all the $^3$He counters. This source had been previously calibrated in the neutron metrology facility of the Physikalisch-Technische Bundesanstalt (PTB
Braunschweig/Germany), which provided the neutron rate with an uncertainty of 1.6%. The obtained efficiency from several measurements is $[35.1 \pm 0.02\text{(stat)} \pm 0.8\text{(syst)}] \%$, in very good agreement with the result of $(34.5 \pm 0.5)\%$ by the MCNPX simulation for the $^{252}\text{Cf}$ case.

![Graph showing neutron detection efficiency vs. neutron energy](image)

**Figure 20:** MCNPX efficiency for the BELEN-30 prototype (2011)[15][A. Riego, Priv. Comm.].

In addition, the source was shifted along the beam axis by 5 and 10 cm and along the vertical axis (centered in the horizontal axis) to study the effect of an extended implantation area. The results are shown in figure 21. A relative change in efficiency of up to few % is observed when the neutrons come from a different position than the center. Notice that the presence of the implantation detector inside BELEN-30 seemed to have an additional small effect on the efficiency (for the common position of 10 cm towards where the beam is coming).

![Graph showing relative change in efficiency along beam and vertical axes](image)

**Figure 21:** Relative change in the efficiency (measured by two parallel DAQs called analog and digital) when the Cf source is shifted from the center, along the beam axis (left) or along the vertical axis (right) in BELEN. The y-values are ratios of efficiency with respect to the one measured in the center (average of more measurements) for both DAQs. Only statistical errors are take into account. The empty symbols correspond to the case when SIMBA was present in BELEN.

Based on these results and being the geometrical span of the silicon detectors of SIMBA
about 6x6 cm, we estimate the uncertainty due to the extended neutron production site to be not more than 1% (relative systematic).

4.2.4 Summary of previous prototypes

The next table (6) summarizes the three BELEN versions used in past experiments between 2009 and 2011 at JYFL and GSI/FRS.

<table>
<thead>
<tr>
<th>Name</th>
<th>$^3$He counters</th>
<th>Pressure (atm)</th>
<th>Experiment</th>
<th>Average efficiency up to 1 MeV</th>
<th>Average efficiency up to 5 MeV</th>
<th>Central hole radius (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELEN-20</td>
<td>20</td>
<td>20</td>
<td>JYFL-2009</td>
<td>30%</td>
<td>27%</td>
<td>5.5</td>
</tr>
<tr>
<td>BELEN-20</td>
<td>20</td>
<td>20</td>
<td>JYFL-2010</td>
<td>45%</td>
<td>37%</td>
<td>5.5</td>
</tr>
<tr>
<td>BELEN-30</td>
<td>20 + 10</td>
<td>20 &amp; 10</td>
<td>GSI-2011</td>
<td>40%</td>
<td>35%</td>
<td>11.5 (SIMBA)</td>
</tr>
</tbody>
</table>

Table 6: Main features of previous experiments

4.3 Summary of detector results: BELEN-48

The presently used intermediate version is BELEN-48. It was designed for experiments at JYFL in 2014 and also used for calibration measurements at the PTB Braunschweig. The design of BELEN-48 is shown in figure 22. It consists of three rings of $^3$He counters around the beam hole. The counters specifications and the matrix material are detailed in tables 7 and 8. The geometrical distribution of the counters among the rings is explained in table 9.

![Figure 22: Design for BELEN-48 detector.](image)

The neutron detection efficiency obtained with MCNPX simulations is presented in figure 23a. The total efficiency stays almost flat up to 2 MeV neutron energy. A detailed view of the
Table 7: Characteristics of the available $^3$He counters.

<table>
<thead>
<tr>
<th>Counter</th>
<th>Property of</th>
<th>Gas</th>
<th>Amount available</th>
<th>Physical and effective length (mm)</th>
<th>Physical and effective diameter (mm)</th>
<th>Gas pressure (atm)</th>
<th>Operating voltage (V)</th>
<th>Cathode material</th>
</tr>
</thead>
<tbody>
<tr>
<td>252248</td>
<td>UPC</td>
<td>$^3$He</td>
<td>38</td>
<td>675.9 / 600.0</td>
<td>25.4 / 24.38</td>
<td>8</td>
<td>1500</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>LND inc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>252248-10</td>
<td>GSI</td>
<td>$^3$He</td>
<td>10</td>
<td>675.9 / 600.0</td>
<td>25.4 / 24.38</td>
<td>10</td>
<td>1500</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>LND inc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Polyethylene properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical compound</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD-PE</td>
<td>CH$_2$</td>
<td>0.95</td>
</tr>
</tbody>
</table>

total efficiency is depicted in figure 23b. To conclude, the criteria are accomplished since the average neutron detection efficiency is around a 45% and the planarity of the efficiency, defined as the maximum value of the neutron detection efficiency divided by the minimum value, is 1.07. Below, the neutron detection MCNPX efficiency is plotted, but extending the energy range up to 5 MeV (figure 24). Considering possible neutrons up to 5 MeV, the average efficiency decreases to 43%, while the planarity increases up to 1.31. A summary can be seen in table 10.

<table>
<thead>
<tr>
<th>Units in mm</th>
<th>Central hole</th>
<th>Rings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inner</td>
<td>Central</td>
</tr>
<tr>
<td>Diameter</td>
<td>160</td>
<td>220</td>
</tr>
<tr>
<td>Counter holes diameter</td>
<td>-</td>
<td>27.5</td>
</tr>
<tr>
<td>Number of $^3$He counters at 10 atm</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Number of $^3$He counters at 8 atm</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 9: Configuration details of BELEN-48 detector.
Figure 23: Neutron detection MCNPX efficiency for BELEN-48 detector up to 2 MeV.

Figure 24: Neutron detection MCNPX efficiency for BELEN-48 detector up to 5 MeV.

<table>
<thead>
<tr>
<th>Energy range</th>
<th>Average efficiency</th>
<th>Planarity factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 keV → 2.0 MeV</td>
<td>45%</td>
<td>1.07</td>
</tr>
<tr>
<td>0.1 keV → 5.0 MeV</td>
<td>43%</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Table 10: Summary of BELEN-48 detection MCNPX efficiency and planarity for different energy ranges up to 2 MeV and 5 MeV.
5 Technical specifications and design details

5.1 Electronics and Triggerless Data Acquisition System

The electronic scheme for BELEN-48 is presented in figure 25. Each proportional counter is connected to one of the inputs of a MPR16-HV Preamplifier (PA) from Mesytec (16 channels). Since the BELEN-48 detector includes 48 counters, three PA are required. Two double output HV modules connected to the preamplifier supply the power to all the counters connected. These preamplifiers are designed to have minimal noise and the output is provided on a differential line. The differential outputs of the preamplifiers connect to a STM16+ Shaping Amplifier (SA) from Mesytec (16 channels). In order to test the acquisition live time, a fixed low frequency (10 Hz) pulse generator can be connected to the preamplifier. The output of the amplifier is sent to the data acquisition (DACQ) system.

![Figure 25: Electronic modules for BELEN-48.](image)

Due to the moderation path of neutrons in polyethylene, the correlation time between the neutron and the beta signal can be up to some microseconds. Due to this moderation caused delay, an opening of a beta-gate signal of such length will introduce considerable dead time in the system. For conventional acquisition systems, a multihit TDC is used to register the time of occurrence but then it makes impossible to distinguish the double neutron emission cases.

In order to avoid this effect in the acquisition system, and therefore to improve its efficiency, a self-triggered or triggerless DACQ system has been developed by the group of IFIC specifically for the BELEN detector [17]. ADCs from STRUCK SIS3302 are used with a 10 ns resolution to implement the system. The main advantage of this system is that the offline analysis can use all the information acquired without time depending signals. The DACQ system includes the GasificTL software fully developed at IFIC.

Every signal in an ADC channel above a given threshold provides a time mark (in 10 ns steps with a range of 48 bits) and starts the energy filter that provides the signal amplitude. Module control and data transfer to a PC occurs via the Struck SIS1100/3100 PCI/VME interface. Each channel stores the time-amplitude data pairs into a 64 MB memory. The memory space is divided into two data banks which are working in alternating mode: while one data bank is filled with the incoming data, the other one is being read-out through the VME bus. In this way a minimum system dead time is achieved. The gasificTL DACQ software allows the configuration and control of the system and performs the online analysis and visualization of the data to run the experiment. In this way large time windows and several correlation modes can be defined in order to achieve an optimal determination of the true coincidences.

A summary of the electronic components is shown in table 11. The connections between the $^3$He counters and the preamplifiers is presented in figure 26.
<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Minimum amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamplifier</td>
<td>Mesytec MPR-16</td>
<td>3</td>
</tr>
<tr>
<td>Amplifier</td>
<td>Mesytec STM-16+</td>
<td>3</td>
</tr>
<tr>
<td>Analog-to-digital converter</td>
<td>Struck SIS3302</td>
<td>6</td>
</tr>
<tr>
<td>High voltage supplier</td>
<td>NHQ203M (2ch)</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 11: BELEN-48 list of electronic components.

Figure 26: Detailed view of connections between counters and preamplifiers.
5.2 Detector construction

The BELEN-48 detector mainly consists of a block of polyethylene and $^3$He proportional gas counters. Whilst the counters are going to be provided by UPC and GSI, the complete polyethylene structure (matrix and shielding) will be probably constructed at GSI.

The polyethylene matrix is composed of 8 slices or blocks of 10 cm thickness that are assembled together to conform the central block with dimensions 50 x 50 x 80 cm$^3$. Except the first block (A), that has only the beam hole, the next 6 blocks (B) are pierced also with the holes for the counters. The rear block (block C), is pierced like a block B but the counter holes are threaded to screw caps. The caps are used to fix the counters inside the holes. The blocks are held together by two stainless steel bars. A technical drawing of a block B is presented in figure 27. The dimensions of a screw cap are shown in figure 28.

![Figure 27: Front view of a single block B.](image)

The shielding consists of different polyethylene blocks adding 20 cm more of polyethylene thickness per side to the matrix. Hence, the total dimensions of the polyethylene structure are 90 x 90 x 80 cm$^3$.

A mechanical test has been done at the UPC workshop to find the minimum distance between the counter holes in order to prevent possible problems during the manufacturing of the polyethylene. Although the drilling tool of GSI could be different to that of UPC, a minimum thickness between counters of 3 mm has been set to avoid mechanical failures of the polyethylene matrix. This aspect is considered as a constraint to be taken into account to define the distribution of counters in the matrix.

A supporting structure for the polyethylene block is going to be designed and constructed at the workshop of the UPC. This structure will be adapted to the final design of BELEN-48, the facility and the implantation detector. During the GSI experiment in 2011 at the FRS such a structure was not required since the full detector setup was placed on the existing FRS
rail structure and only slightly adjusted to the beamline center of 198 cm. However, below, a possible structure is described. It consists of a mobile stainless steel table with a sliding tray to place the detector on. This sliding tray can be moved through a stirring wheel connected to a worm gear system that allows moving the detector precisely in order to center the detector respectively to the beam implantation spot. A technical draw of the possible support structure is presented in figure 29 with its main dimensions. Figure 30 shows a 3D CAD view of the complete setup (BELEN-48 detector and support structure).
Figure 30: 3D view of the BELEN-48 detector placed on its supporting structure.
5.3 Background and shielding

One of the drawbacks of this type of detectors is the loss of information on the energy of the neutron and on its spatial origin due to the moderation in polyethylene. This makes it impossible to single out neutrons coming from the background and requires the detector to be as shielded as possible against background neutrons. This neutron background can have two origins: cosmic radiation and the one caused by the high-energy beam impinging on other beam elements.

Monte Carlo simulations have been carried out to study the detection of background neutrons. The goal of this analysis is to determine the maximum neutron background flux inside the laboratory to assure that the detection of background neutrons is lower than an imposed factor $F$. The background factor $F$ and the neutron background flux $\varphi_B$ are defined as:

$$F = \frac{\text{Sample counts}}{\text{Background counts}} = \frac{N_d}{N_B} = \frac{I_{n,s} \cdot \eta_n}{\varphi_B \cdot S_{det} \cdot \eta_B}$$  \hspace{1cm} (1)

where:

- $N_d$ and $N_B$ are the count rates for a point sample source and the background in cps.
- $I_{n,s}$ is the intensity of the neutron source in n/s.
- $\varphi_B$ is the background neutron flux in $n \cdot s^{-1} cm^{-2}$.
- $\eta_n$ and $\eta_B$ are the detection efficiencies for a point sample source and a background source in %.
- $S_{det}$ is the external surface of the detector in $cm^2$.

Therefore, we impose a factor $F$ equal to 100. In short, the amount of background neutrons detected must be lower than the 1% of the sample neutrons detected. Hence, it is necessary to know both efficiencies and $I_{n,s}$ to be able to set the maximum value of $\varphi_B$. The two efficiencies have been found using Geant4 simulations. These simulations consist of the study of the neutron detection in BELEN-48 modelling a background field of neutrons instead of the point source. The neutron background field is characterized as a spherical surface source with the detector placed inside. The neutrons are emitted inwards radially from the external surface. Figure 31 contains a simple draw of the simulation setup. It is important to note that a sphere emitting neutrons radially from its surface does not correspond exactly to a background field. However, this case can be considered as the worse case, and indeed if the criterion is defined for the worse case, it will be accepted for all the other less-critical cases.

It can be seen how the background detection increases with the energy of the neutrons, specially in the most external counters (figure 32). Nevertheless, for low energy neutrons, the first ring has a greater proportion of detection due to its greater solid angle for the neutrons emitted from the front and the rear of the detector and the lower polyethylene length in those sides.

To evaluate properly the information obtained in the simulations the neutron energy range is divided in three groups: low energy (from $10^{-4}$ MeV to $10^{-1}$ MeV), medium energy (from $10^{-1}$ MeV to 1 MeV) and high energy (from 1 MeV to 5 MeV). Therefore, depending on the neutron background spectrum in the laboratory, one or another equation (2, 3 or 4) will be used to determine the maximum background permitted to achieve a minimum value of $F$ equal to 100. The results are extracted from the equation 1 and the set of detection efficiencies for both
Figure 31: Simulation draw of the background analysis setup

Figure 32: Background detection in GEANT4
configurations (point sample source and background source). \( S_{\text{det}} \), that represents the external surface of the detector, has a value of 48600 cm\(^2\).

\[
\varphi_{B,L,\text{Max}} (n \cdot s^{-1} \cdot cm^{-2}) = \frac{I_{\text{n,s}} \cdot \eta_n}{\eta_B \cdot S_{\text{det}} \cdot F} = 4.623 \cdot 10^{-5} \cdot I_{\text{n,s}} \tag{2}
\]

\[
\varphi_{B,M,\text{Max}} (n \cdot s^{-1} \cdot cm^{-2}) = \frac{I_{\text{n,s}} \cdot \eta_n}{\eta_B \cdot S_{\text{det}} \cdot F} = 1.580 \cdot 10^{-5} \cdot I_{\text{n,s}} \tag{3}
\]

\[
\varphi_{B,H,\text{Max}} (n \cdot s^{-1} \cdot cm^{-2}) = \frac{I_{\text{n,s}} \cdot \eta_n}{\eta_B \cdot S_{\text{det}} \cdot F} = 1.790 \cdot 10^{-6} \cdot I_{\text{n,s}} \tag{4}
\]

where:

- \( \varphi_{B,L,\text{Max}} \) is the background neutron flux for the low energy group.
- \( \varphi_{B,M,\text{Max}} \) is the background neutron flux for the medium energy group.
- \( \varphi_{B,H,\text{Max}} \) is the background neutron flux for the high energy group.

6 Radiation environment and safety issues

The BELEN detector will be used in a place with low intensity primary and secondary radioactive ion beams. However, due to its moderate intensity, no specific radiation safety actions are foreseen except for the implemented restricted access procedure for the site during beam times.

The use of this detector involves several calibration neutron sources such as \(^{252}\text{Cf} \), Am-Be, or other neutron emitters in order to verify that the detection system works properly before the experiment itself. These sources, as neutron emitters, must be controlled by the radioprotection service of the laboratory which will be responsible to provide the dosimeters or the devices needed to control the dose received by the workers or other technicians.

The BELEN detector is composed of high pressure (8-10 atm) \(^3\text{He} \) gas-filled stainless steel tubes. \(^3\text{He} \) gas is classified as hazard type 2.2 (i.e. Non-flammable, non-poisonous compressed gas) according to the United Nations Committee of Experts on the Transport of Dangerous Goods. Hence, the \(^3\text{He} \) counters have to be declared as dangerous goods UN 1046 when shipping (details on figure 33) and properly labelled as explained in section 10.

<table>
<thead>
<tr>
<th>NATURE AND QUANTITY OF DANGEROUS GOODS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UN or ID No.</strong></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>UN1046</td>
</tr>
</tbody>
</table>

Figure 33: Dangerous goods declaration for \(^3\text{He} \) counters.

Besides the \(^3\text{He} \) counters, BELEN does not include any cryogenic cooling devices or other mechanical hazards, the latter to the best of our knowledge. The high-voltage supplies for the counters will be below 2 kV. Furthermore, the probability of the polyethylene to undergo neutron activation (i.e. produce radioactive isotopes such as \(^{14}\text{C} \)) is significantly low due to the low intensity of neutrons emitted.
Regarding the decommissioning of the detector, mainly all of the components can be reused in new experiments. Due to the inert nature of the $^3$He gas, a leakage from a counter has no impact to the environment. The electronic components will be reused in other experiments and finally disposed properly according to the Waste Electrical and Electronic Equipment Directive (European Community directive 2002/96/EC). It is not planned to dispose the polyethylene components since it is not a degradable material and can be reused in other experiments. If needed, it can be recycled with an index 2 from the resin identification coding system.

7 Production, quality assurance and acceptance tests

The BELEN prototypes used at JYFL were constructed at UPC and thus the polyethylene matrices were produced in the UPC workshop. The polyethylene slices were cropped and adjusted to the exact dimensions using a CNC vertical mill machine. The same machine was used to drill the holes in the matrix blocks. An horizontal lathe was used to drill the screw caps (similar to figure 28). General tolerances for linear measures according to DIN ISO 2768-m were applied during the manufacturing of the polyethylene.

During the polyethylene manufacturing process, a greater accuracy is required for the piercing of the holes than the cutting operations due to the importance of the correct placement of the counters inside the matrix.

Regarding the polyethylene composition, a narrow tolerance is accepted beyond the features defined in table 8.

Finally, before the delivery of the BELEN detector to FAIR, all the system components will be tested with respect to their specifications by the BELEN collaboration. Once delivered, further tests will be conducted by the collaboration to verify safe delivery and compatibility with other DESPEC detector systems and FAIR infrastructure.

8 Calibration with test beams

Calibration tests have to be done for each experimental campaign to assure the correct operation of the detector before starting the measurements. Calibration of the BELEN-48 detector can be performed with isotropic neutron sources such as $^{252}$Cf, Am-Be, etc., which produce neutrons in a continuous spectrum. However, it is preferable to use neutrons with narrower energy spread from specific reactions such as the presented in table 12. In this manner, the neutron detection can be validated in different parts of the range of energies instead of based just on a single energy-integrated efficiency value (for the case of using neutron sources).

This approach has been used at the neutron metrology facility in PTB (the Physikalisch-Technische Bundesanstalt Braunschweig, the german metrology laboratory), where it is possible to perform studies also on the neutron angular distribution for each energy and target. Such information is taken into account in the calibration of the detector. Table 12 shows some of the reactions that could be done at PTB.

Another option for the calibration tests can be the use of the detector for measuring the Pn of well-known isotopes (as an example, the IAEA has suggested some calibration standards, like $^{95}$Rb, $^{94}$Rb, or $^{137}$I) at facilities like JYFL (Finland) or RIKEN (Japan).

Calibration at PTB (June-2013) Measurements with a radioactive source emitting neutrons allow to check only one integrated efficiency value, which results from the detection of
Table 12: Possible validation reactions. Laboratory frame projectile energy $E_{proj}$, average neutron energy $<E_n>$, and width of the neutron energy distribution $\Delta E_n$ [18].

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_{proj}$ (MeV)</th>
<th>$&lt;E_n&gt;$ (MeV)</th>
<th>$\Delta E_n$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$B(α,n)</td>
<td>0.606</td>
<td>0.56</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{13}$C(α,n)</td>
<td>1.053</td>
<td>2.8</td>
<td>0.31</td>
</tr>
<tr>
<td>$^{13}$C(α,n)</td>
<td>1.585</td>
<td>3.2</td>
<td>0.41</td>
</tr>
<tr>
<td>$^{51}$V(p,n)</td>
<td>1.80</td>
<td>0.23</td>
<td>0.014</td>
</tr>
<tr>
<td>$^{51}$V(p,n)</td>
<td>2.14</td>
<td>0.56</td>
<td>0.024</td>
</tr>
<tr>
<td>$^{51}$V(p,n)</td>
<td>2.27</td>
<td>0.68</td>
<td>0.028</td>
</tr>
</tbody>
</table>

neutrons with a large distribution in energy. A more stringent test on the simulated efficiency curve requires several data points in a wide energy range. Therefore it has been decided to calibrate the detector with (p,n) and (α,n) reactions on $^7$Li, $^{13}$C and $^{51}$V producing neutrons with a known (limited) spread in energy, ranging from 0.1 to 5 MeV.

The BELEN-48 detector in the configuration with a 110 mm diameter hole and expected 40% efficiency up to 2 MeV was installed at the end of one beam line at the neutron metrology facility of the Physikalisch-Technische Bundesanstalt (PTB Braunschweig/Germany), with the target holder at the center of the detector. On a parallel beam line it was possible to measure reaction yields and angular distributions with calibrated neutron detectors and then to produce the same neutron flux inside BELEN-48, with very similar target and beam conditions. The neutron energy and angular distributions need to be taken into account when comparing the simulated value for each reaction and beam energy to the obtained experimental data. The preliminary results, obtained from the measurements done in June-2013, seem to confirm the simulated efficiency curve for this version of the detector, thus adding another validation test of our simulating capability.

9 Civil engineering and cave

It is requested a suitable area of 3 x 3 m$^2$ to place the detector, the support structure and the electronics and data acquisition system. In addition there should be enough space to be able to mount and demount the detector easily. Figure 34 shows approximately how the BELEN-48 area would be.

The maximum distance between the matrix and the electronic case is 3.5 m. The cables between the preamplifiers and the amplifiers are 5 m long.

The weight of the detector will be around 1 ton, mainly due to the polyethylene moderator. Therefore a suitable ground floor will be required to bear this mass. The room temperature must not exceed the temperature limits defined in the technical specifications of the $^3$He counters and the electronic components.

Finally, other requirements for the infrastructure of the experimental area are:

- Electrical power for experimental equipment only with high quality ground reference (single point grounding).
- A crane to lift up and transport a 1 ton mass, only if a re-adjustement of the polyethylene matrix without any $^3$He counters is required, e.g. the installation of additional shielding.
Figure 34: Plan view of the BELEN-48 site.

- Dedicated Gbit network infrastructure for experimental data transfer and experiment control.

10 Installation procedure and logistics

The BELEN-48 detector has been designed to be assembled around the beam line. The main steps of the installation procedure are introduced below:

1. Center the support table under the output of the beam line and spread out the security belts.

2. Start placing the bottom shield blocks.

3. Place the matrix blocks and held them together with the two bars.

4. Place the side and top shield blocks.

5. Tighten the security belts to fix safely the shielding blocks around the matrix.

6. Accurately center the detector to the beam spot using the stirring wheel of the supporting table.

7. Insert the counters to the polyethylene matrix holes. Tight the screw caps or the subjection system.

8. Plug the SHV connector of each counter tube to the preamplifier input. Preamplifiers must be located close to the polyethylene matrix according to the length of the HV cables (0.75 m in previous BELEN prototypes).

9. Connect the rest of the electronic modules (HV sources and shapers) to the preamplifier according to the scheme presented in section 5.1.
10. Check the output signal of the shaper for each channel with an oscilloscope to verify the expected signals and the threshold to be set in order to avoid the noise. A neutron source can be used in this step.

11. Plug in all the output connectors from the shaper to the ADCs.

12. Verify the proper acquisition in the read-out software.

(a) Label for $^3$He counters.  
(b) Label for electronic components.

Figure 35: Labels for the BELEN-48 transport.

The transportation of the BELEN-48 detector will be done by standard procedures of partially highly fragile instruments from the various assembly and test laboratories. The polyethylene components should be sent taking in care the heavy weight. The $^3$He counters must be sent with an approved package according to the dangerous goods declaration requirements (defined in section 6) and properly tagged with the specified label (figure 35a). The electronic components can be considered as fragile instruments according to their technical specifications and thus they should be transported with a fragile label (figure 35b).
11 Time schedule table and milestones
<table>
<thead>
<tr>
<th></th>
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<td>Design of a prototype with 20 counters at 20 atm (BELEN-20)</td>
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<td>Construction of BELEN-20 polyethylene matrix at UPC</td>
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<td>Test of DAQ for BELEN-20</td>
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<td>Design of a new prototype (BELEN-20) with higher efficiency</td>
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<td>Background test at GSI S4 experimental Hall with single matrices</td>
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<td>Change 21 He-3 counters at 20 atm to 42 counters at 8 atm</td>
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<td>Test of DAQ for BELEN-48 prototype at UPC and GSI</td>
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<td>Data analysis of experiment at IGISOL with BELEN-48 prototype</td>
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<td>Design of BELEN-48 detector for HISPEC/DESPEC adapted to AIDA</td>
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<td>Design and construction of a supporting structure for BELEN-48</td>
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<td>Ready for DESPEC experiments (Fully operational)</td>
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References


