Monte-Carlo Simulations of Neutron Shielding for the ATLAS Forward Region

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Abstract

The effectiveness of different types of neutron shielding for the ATLAS forward region has been studied by means of Monte-Carlo simulations and compared with results of an experiment performed at the CERN PS. The simulation code is based on GEANT, FLUKA, MICAP and GAMLIB. GAMLIB is a new library including processes with γ-rays produced in (n,γ), (n,n'γ) neutron reactions and is interfaced to the MICAP code. Effectiveness of different types of shielding against neutrons and γ-rays, composed from different types of material, as pure polyethylene, borated polyethylene, lithium filled polyethylene, lead, iron, were compared. The results from Monte-Carlo simulations were compared to the results obtained from the experiment. The simulation results reproduce the experimental data well. This agreement supports a correctness of the simulation code used to describe the generation, spreading and absorption of neutrons (up to thermal energies) and γ-rays in the shielding materials. The simulation code provides a powerful tool which allows the extrapolation to the ATLAS forward region of the shielding concept tested at the CERN PS. Based on the results of Monte-Carlo simulations, the comparison between various proposed types of neutron and γ-rays shielding for the ATLAS forward region is presented.

1 Introduction

Experimental tests devoted to the optimisation of the neutron shielding for the ATLAS forward region were performed at the CERN Proton Synchrotron (CERN PS) [1]. A

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collimated beam of 4 GeV/c protons struck into a block of iron (40x40x80 cm^3), which was shielded from one side by different types of shielding. Spectra of neutrons and γ-rays were measured by a Bonner spectrometer and a HPGe detector, respectively.

The aim of the present study is to compare the results of simulations performed using a code based on GEANT, FLUKA, MICAP and library GAMLIB with data obtained from the CERN PS experiment performed to determine experimentally the efficiencies of various types of shieldings against neutrons and γ-rays produced in hadronic cascades confined in a massive iron block.

The Monte-Carlo simulation code GEANT [2] developed at CERN, allows the simulation of the particle shower generation and propagation inside a medium with a complicated geometry or composition. To follow hadrons inside matter, GEANT is interfaced to FLUKA [3, 4], GHEISHA [5] and MICAP [6] codes. In particular, MICAP allows the simulation of neutron propagation and interaction within an energy region from 20 MeV down to 10^{-5} eV. It utilizes data such as cross-sections, angular distributions and secondary energy distributions from the nuclear data file ENDF/B-VI. The MICAP code had to be improved to describe adequatly the generation of γ-rays by neutrons. To achieve this goal, the new library GAMLIB was added to the existing MICAP code libraries. GAMLIB contains spectroscopy data of γ-rays from radiative capture (n,γ) and inelastic scattering (n,n'γ) of neutrons. Table 1 shows a list of isotopes and radiative processes included in the GAMLIB library. These processes represent dominant modes of interaction of neutrons with subsequent γ-rays production in the shielding and detecting materials. The GAMLIB library has been created in CENBG Bordeaux in the framework of the experiment NEMO [7], which is looking for neutrinoless double beta decay of ^{100}Mo. At present, an article about the GAMLIB library is being prepared and will be published separately.

The comparison of the results of the PS experiment and the Monte-Carlo simulations based on above mentioned codes demonstrates the correctness of the simulation code in describing the generation and interaction of neutrons and γ-rays in the shielding materials. It provides a powerful tool which allows the extrapolation to the ATLAS forward region of the shielding concept tested at the PS. Based on the results of the Monte-Carlo simulations the idea of the segmented shielding [1, 8] for the ATLAS forward region and its merits over other proposals has been confirmed.

2 Geometry and materials of Monte-Carlo simulations

The Monte-Carlo simulations were performed using the geometry of the experiment conducted at the PS. The experimental setup includes (Fig. 1) :
-an iron block 40x40x80 cm^3,
-a polyethylene shields of various types (pure polyethylene - PE, borated polyethylene - BPE, lithium filled polyethylene - LiPE) with thicknesses of 8 or 16 cm,
-an optional iron/lead shield with a thickness of 5 cm.
Protons with momentum 4 GeV/c were directed onto the iron block. The compositions of the various types of polyethylene, iron and lead shields are given in Table 2. The same type of iron was used in the block and iron shield. The full description of the PS experiment with the results obtained were published elsewhere [1].

The simulations do not take into account the experimental zone environment, such as various experimental equipment, the walls and the floor of the zone. The beam size is neglected.

3 Neutron production and shielding

In the simulations, the neutrons are followed from their birth up to the end of their life (absorption in the shielding or in the iron block). The neutron absorption is accompanied by production of γ-rays (e.g. 478 keV from B, 2223 keV from H, 7631 keV+7645 keV from Fe). The knowledge of the location where the neutron terminated its life is important for the understanding of the neutron shielding function. This information is also important to assess the need for additional gamma-shielding. During the Monte-Carlo simulations the information about the positions where neutrons as well as γ-rays were born or disappeared due to neutron capture or other interactions is recorded in order to qualify the effectiveness and functionality of shielding layers. The positions were saved in 2-dimensional scatter plots.

The results obtained for born neutrons are shown in Fig. 2. Most of the neutrons were produced in the hadronic cascade inside the iron block and the optional Fe or Pb shielding which is put against γ-rays. The number of neutrons born in the polyethylene part of the shielding (PE, BPE, LiPE) is negligible compared with the number of neutrons generated in the iron block and is approximately the same for all types of polyethylene layers. The number of neutrons born in the Pb outer layer of shielding is 3 times higher compared with outer layer part of shielding made of Fe.

The results obtained on the number of stopped of neutrons in the shielding are shown in Fig. 3. In the case of the shielding made of pure PE, which is the most efficient fast neutron moderator, many of the neutrons die in PE itself while some are absorbed in the iron layer close to PE, due to the radiative capture of albedo neutrons (see Fig.3 - PE 16 cm). Hence, pure PE shielding gives better suppression of leaking neutrons over most of the neutron energy regions, as expected. However, the slow neutron capture by H and Fe is responsible for a massive production of high energy γ-rays, of them the most dominant are 2.2 MeV photons, against which it is difficult to deploy shielding. This will be shown and discussed in the next section.

If polyethylene is doped with boron (BPE) or lithium (LiPE), the neutrons are absorbed predominantly by these nuclei due to their high neutron capture cross section. Consequently, absorption of neutrons by H and absorption of albedo neutrons by Fe is suppressed. However, in the case of BPE, an intensive production of 478 keV photons will take place. These photons can be easily shielded against. Negligible amount of photons accompany neutron absorption in the lithium doped polyethylene. The best suppression of neutrons (the maximum number of stopped neutrons) is achieved for the shielding with BPE. The effectiveness of the PE and the LiPE shieldings at suppressing neutrons is 75% and 95% of that of the BPE shielding, respectively (see Fig. 3).

Monte-Carlo simulations produced the spectra of leaking neutrons from the shielding as well as the leaking γ-rays. The whole neutron energy region was subdivided into five regions - 0-10 keV, 10-100 keV, 100-1000 keV, 1-10 MeV and above 10 MeV. The results obtained are given in Table 3. This table shows that the lowest total number of leaking neutrons in configuration with layer against γ-rays is achieved for 8 cm of BPE + 5 cm of Fe + 8 cm of LiPE (segmented shielding). The shielding made from 16 cm of BPE + 5 cm of Pb leads to an increase by a factor 1.6 of the total number of leaking neutrons. This increase is mostly caused by neutrons from lead spallation. Adding 8 cm to the polyethylene thickness leads to an increase of the shielding effectiveness at absorbing neutrons. According to Table 3, the doubling of BPE thickness in the segmented shielding will further improve the segmented shielding function. When an iron layer 5 cm thick is added as supplementary γ-ray shielding, only a small fraction of neutrons, which passes through BPE or LiPE, is captured in this additional iron layer. Then the number of high energy γ-rays generated in this additional layer is small.

An example of bad combination of layers for neutron shielding from the point of view of suppressing of γ-ray production is the use of PE layer together with an extra iron layer (see further). The neutrons moderated inside PE are not all captured. Therefore, they are escaping back to the neighbouring iron layer where they are mostly captured by iron, inducing high energy γ-rays.

4 Gamma-rays production and shielding

The appearence, transport and disappearence of photons generated in the hadronic cascade and the subsequent processes were also simulated. The simulation program recorded energy spectra of the γ-rays exiting an outer side of the shielding as well as the information about the positions where γ-rays appeared or disappeared. An attention was devoted to the γ-rays, which characterise the dominant processes in shielding materials. Particulary, the following γ-rays were monitored: 478 keV from the ^{10}B(n,α) reaction, 847 keV from the ^{56}Fe(n,n$'\gamma$) reaction, 2223 keV from the ^{1}H(n,γ) reaction and 7631 + 7645 keV doublet from the ^{56}Fe(n,γ) reaction. The positions were again saved in 2-dimensional scatter plots.

The results obtained concerning the birth of γ-rays in shielding layers are shown in Fig. 4. The number of born γ-rays in the LiPE neutron shielding is less by an order of magnitude compared with either the BPE or the PE shieldings.

The results related to the stopping of γ-rays are shown in Fig. 5. It can be seen that the number of γ-rays stopped in the low Z part of the shielding itself is negligible. One can also recognize a higher suppression efficiency of Pb compared with Fe, especially for the 478 keV γ-peak of boron (factor $\sim$2.5).

The Monte-Carlo simulations produced the spectra of leaking γ-rays. As it was the case for neutron studies, the whole γ-ray energy region was subdivided into several regions - 0-100 keV, 100-1000 keV, 1-10 MeV and over 10 MeV. The results obtained are summarized in Table 4. It shows that the overall best suppression of leaking γ-rays is achieved for 16 cm of BPE + 5 cm of Pb. One can see that the adding of iron layer in the shielding as it is the case of 16 cm of BPE + 5 cm of Fe and of the segmented shielding (8 cm of BPE + 5 cm of Fe + 8 cm of LiPE) suppresses leaking γ-rays also significantly. The total number of leaking γ-rays formed with the best shielding is a factor 5 lower than the number achieved with the segmented shielding. However, as previously stated, the doubling of BPE thickness should achieve better neutron absorption. Accordingly, it suppresses also a number of leaking 478 keV γ-rays due to selfabsorption, see Table 5. The shielding suppression should be further possibly reinforced by a thicker layer of iron.

A comparison was performed between relative areas of γ-ray peaks obtained in the PS experiment and those obtained from the Monte-Carlo simulations. This comparison has confirmed a correctness of the description of the physical processes implemented in the Monte Carlo simulations extended by GAMLIB capability to describe the various shielding functions over the whole neutron and γ-ray energy ranges. The results for dominant spectral peak areas are given in Table 5. The values of peak areas were normalised to the maximal value for every energy separately. One can find a good agreement of attenuation factors between Monte-Carlo simulations and experiment. It has to be stressed, however that the experimental values are affected by background from the experimental hall, especially for an effective shielding [1].

In the case of pure PE, the 2223 keV γ-peak produced by thermal neutron capture on H dominates. The high energy peaks resulting from neutron capture on Fe (7631 keV and 7645 keV) are also produced intensively, as can be easy recognized in Fig. 6 and in Table 5. Peak at the energy of 847 keV demonstrates which amount of fast neutrons undergo inelastic scattering on Fe nuclei before they become moderated.

When PE is replaced by LiPE, a significant suppression of the H peak (2223 keV) as well as a suppression of high energy γ-rays from neutron capture on Fe are observed, as expected. It is a significant advantage of LiPE over BPE, that neutron absorption is not accompanied by an additional γ-ray production. The 847 keV peak originating from inelastic scattering on Fe remains approximately the same.

If BPE is used, the data in Table 5 show a suppression of both the H peak and the high energy γ-lines from neutron capture on Fe, as it was in the case of LiPE shielding. As the cross section of thermal neutron capture on B is greater than the one on Li, the suppression is improved significantly. On the other hand, the intensive generation of 478 keV γ-rays from neutron absorption by B remains the only disadvantage of BPE against LiPE as neutron shielding material. However, such relatively low energy γ-rays are partly absorbed by BPE itself and the rest of them can be easily shielded against by an additional layer of material, like Fe. Simulations show that 5 cm of iron is enough to suppress the 478 keV γ-rays from neutron capture on B by a factor of about 50. The suppression by Pb is even substantially larger.

5 Conclusion

The aim of the work was to confirm the idea and effectiveness of the segmented shielding for the ATLAS forward region proposed in [1, 8]. For that the Monte-Carlo simulations were performed taking into account the simple geometry of an experiment done at the CERN PS [1], which served as a benchmark test of various concepts of shielding of neutrons in the ATLAS forward region. In such a way the correctness of the simulations based on GEANT, FLUKA, MICAP and GAMLIB libraries was validated. The results obtained from the Monte-Carlo simulations up to γ-rays detection level are in good agreement with the PS experiment results (see comparing the peak areas of γ-rays from (n,γ) and (n,n$'\gamma$) reactions in Table 5). The results achieved demonstrate that we have a tool which properly describes generation, transport and absorption of neutrons down to thermal energy and γ-rays subsequently produced in the interactions of such neutrons with matter.

The results presented in this article show that the idea of the segmented shielding consisting of BPE, Fe and LiPE layers, which has been proposed in [1, 8] is correct and should be adequate for providing the optimal neutron shielding for the ATLAS forward region. These results help to understand part of whole functionality of any shielding. Segmented shielding is good from the point of view of efficiency in absorbing neutrons and γ-rays and from engineering point of view, as well [10]. Efficiency against neutrons can be improved by increasing the thickness of the BPE layer. Taking into account the space available for shielding in the ATLAS forward region [9], the recommended composition of the segmented shielding should be layers of 25 cm of BPE + 5 cm of Fe + 5 cm of LiPE. BPE possesses better moderation capability than LiPE. B is very efficient at absorbing slow neutrons with, however, production of 478 keV γ-rays against which a 5 cm thick Fe layer provides efficient shielding. The LiPE additional outer shielding layer should act also as a shield against neutrons entering the ATLAS forward region shielding from outside after reflecting by the ATLAS cavern walls and parts of the ATLAS detector.

The extension of the Monte-Carlo simulation to the full ATLAS forward region is presently in progress.

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References

[1] S. Pospíšil, I.Štekl, T.Čechák, P.Čermák, J.Jakůbek, J.Klusoň, J.Kubašta, V.Linhart, M,Šiňor, C.Leroy, Z.Doležal, R.Leitner, G.Lukhanin, K.Soustružník, M.Lokajíček, S.Němeček, J.Palla, J.Sodomka, *Experimental tests of neutron shielding in the ATLAS forward region.* Nucl. Instr. and Meth. in Phys. Res. A 420 (1999) 249.

[2] GEANT, Detector Description and Simulation Tool. CERN Program Library, long writeup W5013, 1994.

[3] P.A.Aarnio et al., *Fluka user's guide.* Technical Report TIS-RP-190, CERN, 1987, 1990.

[4] P.A.Aarnio, A.Fasso, A.Ferrari et al., *A New Model for hadronic interactions at intermediate energies for the FLUKA code.* International Conference on Monte-Carlo Simulation in High-Energy and Nuclear Physics, Tallahassee, Florida, 22-26 February 1993, Publ. in: MC93 : Proceedings P. Dragovitsch, S.L.Linn and M.Burbank World Sci., Singapore, 1994 (88-99).

[5] H.C.Fesefeldt, *Simulation of hadronic showers, physics and applications.* Technical Report PYTHA 85-02, III Physikalisches Institut, RWTH Aachen Physikzentrum, 5100 Aachen, Germany, September 1985.

[6] J.O.Johnson and T.A.Gabriel, *A User's Guide to MICAP: A Monte Carlo Ionization Chamber Analysis Package.* Technical Report TM-10340, ORNL, 1988.

[7] NEMO collaboration: Preprint LAL 94-29 (1994).

[8] C.Leroy, S.Pospíšil, I.Štekl, J.Sodomka, *Remarks on a Concept of the ATLAS forward region shielding.* ATLAS Internal Note, TECH-NO-032, 8 May 1998.

[9] ATLAS: *Technical Proposal for a general-purpose experiment at the Large Hadron Collider at CERN.* CERN/LHC/94-43 (1994).

[10] J.Sodomka, C.Leroy, J.Palla, S.Pospíšil, I.Štekl, *The Shielding of the ATLAS Forward Region from the point of view of Materials Technology and some Construction Aspects.* ATLAS Internal Note, TECH-NO-33, 12 October 1998.

Figure 1: Experimental setup.

Figure 2: Distribution of born neutrons in different types of neutron shielding. The results of Monte-Carlo simulations are given as scatter plots (first and third rows) as well as their projections into histograms (second and fourth rows). The numbers on the horizontal axes are in cm, as well as the numbers on the vertical axis for the scatter plots. The numbers on the vertical axis for the projections are the numbers of neutrons produced per incident proton per bin. The edge of the shielding adjacent to the iron block is placed on the horizontal axis in zero coordinate.

Figure 3: Distribution of stopped neutrons in different types of neutron shielding. The results of Monte-Carlo simulations are given as scatter plots (first and third rows) as well as their projections into histograms (second and fourth rows). The numbers on the horizontal axes are in cm, as well as the numbers on the vertical axis for the scatter plots. The numbers on the vertical axis for the projections are the numbers of neutrons produced per incident proton per bin. The edge of the shielding adjacent to the iron block is placed on the horizontal axis in zero coordinate.

Figure 4: Distribution of born γ-rays in different types of neutron shielding. The results of Monte-Carlo simulations are given as scatter plots (first and third rows) as well as their projections into histograms (second and fourth rows). Only the shielding part of the setup is shown in the figure. The numbers on the horizontal axes are in cm, as well as the numbers on the vertical axis for the scatter plots. The numbers on the vertical axis for the projections are the numbers of neutrons produced per incident proton per bin. The edge of the shielding adjacent to the iron block is placed on the horizontal axis in zero coordinate.

Figure 5: Distribution of stopped γ-rays in different types of neutron shielding. The results of Monte-Carlo simulations are given as scatter plots (first and third rows) as well as their projections into histograms (second and fourth rows). Only the shielding part of the setup is shown in the figure. The numbers on the horizontal axes are in cm, as well as the numbers on the vertical axis for the scatter plots. The numbers on the vertical axis for the projections are the numbers of neutrons produced per incident proton per bin. The edge of the shielding adjacent to the iron block is placed on the horizontal exis in zero coordinate.

Figure 6: Spectra of γ-ray photons escaping different types of shielding. The numbers on the horizontal axes express energy of γ-rays in keV. The numbers of photons, on the vertical axes, are normalized per one initial proton entering the iron block.

Isotopes	(n,γ)	(n,n'γ)
^{54,56,57,58}Fe	+	+
^{27}Al	-	+
^{63,65}Cu	+	+
^{206,207,208}Pb	+	+
^{12}C	+	-
^{113}Cd	+	-
^{19}F	-	+
^{35,37}Cl	-	+
^{72,73,74,76}Ge	+	+

Table 1: Isotopes and processes with γ emission included in the GAMLIB library (+ means included, - means not included). Data about other isotopes were used from the MICAP library.

Material	Density [g/cm^3]	Elemental composition [wt%]				
		H	Li	B	C	O
PE ($(CH_2)_n$)	0.93	14.4	-	-	85.6	-
BPE ($(CH_2)_n$ + 3% of B as H_3BO_3)	0.99	12.7	-	3.0	71.0	13.3
LiPE ($(CH_2)_n$ + 10% of Li as Li_2CO_3)	1.30	6.7	10.0	-	48.7	34.6

Material	Density [g/cm^3]	Elemental composition [wt%]				
		Fe	C	P	S	Pb
iron	7.8	99.87	0.07	0.03	0.03	-
lead	13.2	-	-	-	-	100

Table 2: Elemental composition of materials used in the Monte-Carlo simulations.

	0-10 [keV]	10-100 [keV]	100-1000 [keV]	1-10 [MeV]	$\geq$10 [MeV]	$\geq$10 [keV]	total
8cm PE	120.94	9.31	40.21	49.41	96.94	195.87	316.81
8cm LiPE	118.16	39.56	106.44	71.91	101.45	319.35	437.51
8cm BPE	91.66	33.67	96.31	69.64	100.28	299.99	391.65
16cm PE	11.95	0.88	2.37	8.90	38.45	24.10	62.55
16cm LiPE	17.40	4.48	10.26	16.45	43.02	48.59	91.61
16cm BPE	11.52	3.46	9.01	15.85	42.83	39.84	82.67
16cm BPE+5cm Fe	3.68	2.76	14.46	18.19	29.88	39.09	68.97
16cm BPE+5cm Pb	8.60	3.82	23.61	33.28	30.69	69.31	100.00
8cm BPE+5cm Fe+8cm LiPE	11.24	3.11	7.80	11.42	28.84	33.57	62.41

Table 3: The relative fluxes obtained from the Monte-Carlo simulations for neutrons leaking out the shielding. The values reported in the table for various configurations are normalised to the total number of leaking neutrons in the 16 cm BPE with 5 cm of Pb shielding configuration. In general, an error less than 8% should be attached to each number in the table.

	0-100 [keV]	101-1000 [keV]	≤1 [MeV]	1-10 [MeV]	≥10 [MeV]	≥1 [MeV]	total
8cm PE	9.66	85.98	95.64	102.57	0.85	103.42	199.06
8cm LiPE	3.04	37.68	40.72	28.13	0.82	28.94	69.66
8cm BPE	10.02	109.06	119.07	26.45	0.83	27.28	146.35
16cm PE	12.94	39.13	52.07	47.61	0.32	47.93	100.00
16cm LiPE	38.00	14.22	52.22	9.95	0.33	10.28	62.50
16cm BPE	16.31	61.90	78.21	9.23	0.30	9.53	87.74
16cm BPE+5cm Fe	0.08	7.74	7.82	4.49	0.11	4.60	12.42
16cm BPE+5cm Pb	0.01	1.05	1.06	2.03	0.05	2.08	3.14
+8cm BPE+5cm Fe+8cm LiPE	1.19	9.01	10.20	5.37	0.10	5.47	15.67

Table 4: The relative fluxes obtained from the Monte-Carlo simulations for γ-rays leaking out the shielding. Values in the table obtained for various configurations are normalised to the number of all leaking γ-rays in the case of 16 cm PE shielding. In general, an error less than 8% should be attached to each number in the table.

	B peak area (478keV)		Fe peak area (847keV)		H peak area (2223keV)		Fe peak area (7631& 7645keV)	
	Exp.	M-C	Exp.	M-C	Exp.	M-C	Exp.	M-C
16cm PE	-	-	0.839	0.863	1	1	1	1
16cm LiPE	-	-	0.940	0.981	0.051	0.023	0.357	0.205
16cm BPE	1	1	1	1	0.035	0.014	0.260	0.184
16cm BPE+5cm Fe	0.026	0.017	0.657	0.766	0.007	0.002	0.093	0.056
16cm BPE+5cm Pb	0.005	-1)	0.187	-2)	0.004	0.0006	0.031	0.007
8cm BPE+5cm Fe+8cm LiPE	0.039	0.012	0.706	0.534	0.018	0.0059	0.206	0.122
8cm BPE	1	1	1	1	1	1	1	1
16cm BPE	0.629	0.363	0.615	0.390	0.875	0.500	0.812	0.623

Table 5: Comparison between the Monte-Carlo simulations and experimental results for areas of selected spectral gamma peaks. Peak area values in the table are normalised to the maximal values for every energy separately. - means that data are not available or are on level of background, 1) after 830000 events no photons with energy of 478 keV were observed; 2) after 830000 events only 27 photons with energy of 847 keV were observed, which corresponds to the highest error, 19%, in the table.