Thermal neutron flux measurements in STAR experimental hall.

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Abstract
We report on measurements of thermal neutron fluxes at different locations in the STAR experimental hall during pp \( \sqrt{s} = 510 \) GeV Run 13 at RHIC. We compared these measurements with calculations based on PYTHIA as minimum bias events generator, the detailed GEANT3 simulation of the STAR detector and the experimental hall, and using GCALOR as neutron transport code. A good (within \( \approx 30\% \)) agreement was found at locations near (\( \approx 1 \) m) and very far (\( \approx 10 \) m) from the beam pipe. For intermediate locations (\( \approx 5 \) m) the simulation overestimates neutron flux by a factor of \( \approx 3 \).

Keywords: thermal neutrons, measurements, simulation

1. Introduction
Since the time of R&D for the SSC detectors\textsuperscript{[\textsuperscript{11,2}]} it has been understood that the main source of background in a detector at modern colliders are collisions at interaction point. The contribution from other sources (beam gas interactions, beam halo particles, etc.) estimated to be below 10%\textsuperscript{[\textsuperscript{3}].} Extensive simulations of background conditions were part of detectors optimizations for SSC and LHC experiments. ATLAS\textsuperscript{[\textsuperscript{4}]} and CMS\textsuperscript{[\textsuperscript{5}]} have made simulations for all types of backgrounds including neutrons. Estimations of the neutron fluxes in experimental areas were based on simulations only, without support from experimentally measured data. Only recently the ATLAS-MPX collaboration\textsuperscript{[\textsuperscript{6}]} published results of absolute background measurements in the ATLAS experimental hall including thermal neutrons and made a comparison with results of simulations with GEANT3+GCALOR\textsuperscript{[\textsuperscript{7}]} and Fluka\textsuperscript{[\textsuperscript{8}].} Their conclusion was\textsuperscript{[\textsuperscript{6}]}: “Measured thermal neutron fluxes are found to be largely in agreement with the original simulations, mostly within a factor of two. Significant deviations are observed in the low radiation regions of ATLAS cavern, where measured thermal neutron fluxes are found to be lower than predicted by Monte Carlo simulations.”

The STAR detector at the Relativistic Heavy Ion Collider (RHIC)\textsuperscript{[\textsuperscript{9}]} is planning series of upgrades in the near future with detectors using different types of silicon sensors. Reliable estimations of neutron background at STAR are required to evaluate different technologies for these upgrades. This necessity and the lack of experimental results for neutron background estimations were our motivations for this work. Same questions have been raised in context of ongoing detector R&D for proposed Electron Ion Collider (EIC)\textsuperscript{[\textsuperscript{10}]):

- What are neutron background conditions currently at the STAR detector and will be at EIC?
- How reliable can we estimate these conditions?

To answer these questions we:

- made measurement of the absolute thermal neutron flux at different locations in the STAR\textsuperscript{[\textsuperscript{9}]} Wide Angle Hall (WAH) during RHIC Run 13\textsuperscript{[\textsuperscript{11}].}
- compared experimental results with simulation in order to understand how reliable this simulation is, and
- estimated fluxes of the intermediate energy neutrons using simulation results.

For the purpose of future discussions we will classify neutrons by kinetic energy (\( E_{\text{kin}} \)) as follows:

- intermediate energy neutrons with \( E_{\text{kin}} \) in range 100 keV–1 MeV, which are most damaging for electronics and silicon detectors, and
- thermal neutrons with \( E_{\text{kin}} \) below 250 meV. This definition includes cold (< 25 meV), thermal as such (25 meV), and part of epithermal (25 meV < \( E_{\text{kin}} \) <400 meV) neutrons. The thermal neutrons generate \( \gamma \)-quanta producing noise in detector elements.

2. Measurements

2.1. \((He^3)\) counter
We used a \( He^3 \) filled proportional counter\textsuperscript{[\textsuperscript{12}]} \((He^3C)\), loaned to us by BNL Instrumentation Division, to measure fluxes of thermal neutrons in WAH.

- The thermal neutrons were detected via reaction:
  \[n + He^3 \rightarrow H^1 + H^3 + 764 \text{keV},\]
  with cross section: \( \sigma = 5.4 \sqrt{(25.3 \text{meV}/E_{\text{kin}})} \) [kbarn]\textsuperscript{[\textsuperscript{13}].}
- The \( He^3C \) specification\textsuperscript{[\textsuperscript{12}]} gave the neutron sensitivity 100±10 counts per 1Hz/cm\(^2\) of thermal neutron flux. This sensitivity was measured with calibrated isotropic thermal neutron flux at a temperature of 25\( ^\circ \text{C} \textsuperscript{[\textsuperscript{14}].}\)
The signal was shaped with the threshold set to 20% of the maximum signal (764 keV), which corresponds to an unambiguous thermal neutron registration (contamination of γ and charged particles were due to only multiple hits during signal collection time of the detector $\approx 5 \mu$s and neglected herein).

During the run $He^3C$ was positioned at 6 locations of WAH (Fig 1): the South and North (Fig 2) on the level of the second platform just outside of MTD from the south and north sides of the detector, the Bottom on the floor under MTD (Fig 3 and Fig 4), the West and East near the entrances to the tunnel (Fig 5), and the Far Away (Fig 5) on the floor just after the entrance to WAH.

The shaped $He^3C$ signal was fed to the so called STAR RICH scalers (channel 16), and the rate of the scaler (Hz) was recorded in STAR online database (each 15 s) and in STAR daq.
stream (with frequency 1 Hz) together with others scalers (particularly, ZDC West, ZDC East, and ZDC West and East coincidence). The He$^3$C rate versus date of data taking for different counter locations is shown in Fig.6.

Figure 6: Measured He$^3$C rate (Hz) versus date at different counter locations: South (during period: 03/13-04/03), West (04/03-04/17), East (04/17-05/03), North (05/08-05/22), Bottom (05/23-06/05), and Far Away (06/06-06/10). The location change is marked as red dots.

Table 1: The measured counter rates (C) for different counter locations. The corrected counter rates ($C_C$, see text) per 1 MHz of inelastic events at different locations are given in kHz.

| Location   | $C_C$ (kHz) | $RC (Hz/cm^2)$ | $MC (Hz/cm^2)$ | ratio |
|------------|-------------|----------------|----------------|-------|
| South      | 1.18        | 13.6 ± 1.4     | 34.7 ± 5.9     | 0.39 ± 0.08 |
| West       | 9.15        | 105.2 ± 10.5   | 124.1 ± 11.1   | 0.85 ± 0.11 |
| East       | 12.14       | 139.5 ± 13.9   | 105.3 ± 10.3   | 1.33 ± 0.18 |
| North      | 2.34        | 26.9 ± 2.6     | 39.9 ± 6.3     | 0.67 ± 0.13 |
| Bottom     | 0.66        | 7.6 ± 0.8      | 23.9 ± 4.9     | 0.32 ± 0.07 |
| FarAway    | 0.63        | 7.2 ± 0.7      | 7.0 ± 2.6      | 1.03 ± 0.40 |

Then we used 3 equations:

\[ P_E = P_A + P_{AB} \times (1 - P_A) \]
\[ P_W = P_B + P_{AB} \times (1 - P_B) \]
\[ P_{WE} = P_A \times P_B + P_{AB} \times (1 - P_A \times P_B) \]

and solved them with respect to $P_{AB}$

\[ P_{AB} = \frac{P_{WE} - P_E P_W}{1 + P_{WE} - P_E - P_W} = 1 - e^{-\mu}, \]

where $\mu$ is the mean value of Poisson distribution.

Thus the coincidence rate (AB) corrected for random coincidence for A and B is

\[ N_{AB} = \mu \times N_{BC} = -\ln(1 - P_{AB}) \times N_{BC}. \]

The coincidence rate in ZDC corresponded to $\sigma = 2.81$ mb$^{15}$ from 50 mb of pp$^{13}$ inelastic cross section at $\sqrt{s} = 510$ GeV. Thus the total event rate: $R = 50/2.81 \times N_{AB}$.

2.3. Fluxes

The measured fluxes are obtained from the He$^3$C rate ($C$) using the counter sensitivity. Dependences of the measured C at the different locations on R are shown in Fig.7. In order to normalize C to 1 MHz of pp interaction rate ($C_0$) and also account for saturation effects in He$^3$C due to its dead time, the dependences were approximated by $C = R \times (C_0 + R \times C_1)$. The measurements of $C_0$ for different locations are presented in Table$^{11}$.

2.2. Event rate

In this study we used the East and West ZDC scalers. In order to estimate event rate [MHz] the following approach$^{16}$ $^{17}$ was used:

- $N_{BC} = 9.383 \times 111/120$: number of bunch crossings,
- $N_{WE}$: number of crossings that contain a coincidence of the West and East counters with probability $P_{WE} = N_{WE}/N_{BC}$.

- $N_E$: number of crossings that contain a hit in the East counter, $P_E = N_E/N_{BC}$,
- $N_W$: number of crossings that contain a hit in the West counter, $P_W = N_W/N_{BC}$,
- $P_A$: a probability to produce an East hit,
- $P_B$: a probability to produce a West hit,
- $P_{AB}$: a probability to produce at least one or more East and West coincidences in the beam crossing.
3. Simulation

To estimate fluxes, PYTHIA version 6.4.26[19] as pp 510 GeV minimum biased event generator and GEANT3+GCALOR[7] for propagation particles in WAH were used. The STAR detector and WAH geometry description was taken as version y2013_l1a[20] used for RHIC Run 13. The only two essential changes from default STAR simulation were:

1. reducing $E_{\text{kin}}$ cut for neutral hadrons (CUTNEU) from 1 MeV to $10^{-13}$ GeV, and
2. increasing maximum particle time of flight cut (TOF-MAX) from $5 \times 10^{-4}$ to $1 \times 10^{3}$ s.

The simulated $E_{\text{kin}}$ spectrum of neutrons in WAH and the spectrum convoluted with the neutron cross section are presented in Fig. 8. From this spectrum we can conclude that 87% of neutrons with $E_{\text{kin}} < 250\text{meV}$ were detected by $He^{3}C$.

The neutron’s time of flight distribution from the simulation is presented in Fig. 9. There are two distinct components in the distribution: the first one with $\tau = 7.1$ ms which corresponds to neutron dissipation from WAH and the second component suppressed by a factor of $10^{7}$ with respect to the first one with $\tau = 891s$ which is due to neutron decays (in the simulation neutron life time $\tau = 887s$ was used). Unfortunately, with our maximum recording rate of 1 Hz we could not detect the dissipation component.

The radial dependence of fluxes at $Z \approx 0$ and $Z \approx 675$ cm for all neutrons, neutrons with $E_{\text{kin}} > 100\text{keV}$ and neutrons with $E_{\text{kin}} < 250\text{meV}$ are shown in Fig. 12.

Figure 8: The neutron kinetic energy spectrum in WAH and result of convolution (red dashed line) of this spectrum with $He^{3}$ neutron cross section. The integral of the convoluted spectrum corresponds to 87% of the total spectrum integral in region $< 250\text{meV}$.

Flux was defined as sum of track length of a particle collected in a given volume in unit time divided by the volume size. The fluxes were normalized to 1 MHz rate of pp inelastic events at $\sqrt{s} = 510$ GeV. Fluxes for all neutrons and neutrons with $E_{\text{kin}} < 250\text{meV}$ are show in Fig. 10 and Fig. 11, respectively. The radial dependence of fluxes at $Z \approx 0$ and $Z \approx 675$ cm for all neutrons, neutrons with $E_{\text{kin}} > 100\text{keV}$ and neutrons with $E_{\text{kin}} < 250\text{meV}$ are shown in Fig. 12.

Figure 9: The neutron’s time of flight. The black and green histograms are for all and the thermal neutrons $(E_{\text{kin}} < 250\text{meV})$, respectively. The red line corresponds to exponential fit $e^{-t/\tau}$ with $\tau = 7.1\text{ms}$ and the blue line to fit with $\tau = 891s$.

Figure 10: Neutron flux in WAH.

Figure 11: Thermal neutron $(E_{\text{kin}} < 250\text{meV})$ flux in WAH.
4. Conclusions

From this study we conclude that we can estimate neutron background for STAR detector with good precision. The results of the measurement and simulation are presented with absolute values and their ratios in Table 1. The comparison is good (within 30%) for the West, East and Far Away locations. However, for the South, North and Bottom locations the simulation underestimated flux by a factor of ≈3. This conclusion is very close to one [6] which we cited in the introduction. The mismatch between the measurement and the simulation may be due to inaccurate description of geometry and material in the WAH, which would affect the neutron dissipation from the interaction region. The deviation could also be related to the neutron transport parameters.

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