A reply to PAC37 on the TAC concerns about neutron induced rates in the detectors of the proposed experiments with Super Bigbite, PR12-11-001 and C12-09-018

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The Hall A Technical Review expressed concerns shown below mainly about PMT rates in the Cherenkov counters and suggested evaluating a possible neutron origin of the observed rates:

"**3) The performance of the HERMES RICH in the extremely high luminosity is a concern. The collaboration has attempted to address this in section 3.2.1 of the proposal using a Geant3 simulation for the low-energy photons from the target and the secondary electrons subsequently produced. There is no mention in the proposal how carefully neutrons from the target, beam line, and dump were included; those neutrons can produce electrons above Cherenkov threshold in the radiators of the RICH or in the glass of the PMTs. This point should be clarified. More generally, the ability of the Monte Carlo to predict high-rate particle backgrounds that will affect the detectors, is uncertain, given the history of the Gas Cherenkov during the Transversity experiment (comment 4). At a minimum, significant commissioning time should be foreseen for the RICH in Hall A at varying luminosities.**

4) The experimenters propose to use the Bigbite (BB) Gas Cherenkov (GC) at the trigger level to reduce the rates to a few kHz so that a Fastbus readout of the SBS RICH will work. A Flash ADC with programmable FPGA will be implemented to form a segmented coincidence with adjacent sections of the lead-glass calorimeter. One needs to consider the latency for such a trigger, which might exceed 200 nsec; however, this would not affect the pipelined part of the DAQ. During the Transversity experiment in 2009, with BB at the same angle (30°) and a similar luminosity to this proposal, the BB GC had several problems that are worrisome. To reduce the impact of the fringe field on the PMT, the PMT was pulled deeper into a mu-metal shield, contributing to a lower than desired light yield (7 ph.e. per track). It is thought possible to compensate for the field with bucking coils, but this is unproven. A more serious problem was the high rate of unexplained background on the side of the detector nearest the beam-line, which exceeded by a factor of 10 the expectation and led to a poor performance of the detector during Transversity. The source of background was thought to be from the beam line elements; however, attempts to reduce the rates through shielding were unsuccessful, and attempts to understand this background through simulation have been unsuccessful up to the present time. The proposal has tried to take this uncertainty into account by scaling their rates by a factor of 8 to reproduce the rates during Transversity. Perhaps the missing rate is due to neutrons?"

In the text of proposal C12-11-018 we presented detailed calculation of the PMT rate in the RICH counter, see section 3.2.1 on page 25-29. Here we just present a near quotation from the proposal: “From the results of our calculation of the photon yield, and the experimentally observed fact that the yield of photoelectrons per high-energy charged track in the HERMES RICH counter is about 10, the proper normalization of our calculation for the combined collection and detection efficiency of the setup is approximately 8.7%. From this we conclude that the rate of background hits is about 111 kHz per PMT, or about 1.1% occupancy for a $\pm$50 ns time interval relative to the hadronic calorimeter timing. Using a cost-effective TDC readout with LeCroy 1877 Fastbus (20,000 channels were obtained by the SBS collaboration from CLEO) multi-hit TDCs with 0.5 ns resolution for the PMT hits from the RICH detector, this time window could be reduced to 10 ns or less in the offline analysis, resulting in a low occupancy on the order of 10^{-3}, which would present no problems for the reliable operation of the detector and reconstruction of events.”

The rate of the PMTs in the BigBite spectrometer was also calculated (see more below). To check the reliability of MC model the rate was calculated also for MWDC (see more below). This document also addresses the concern about the neutron induced rate due to the borosilicate PMT window.

1 Neutron flux at the detector location

The first key needed for analysis of the neutron induced rate of the detectors is a neutron flux at the detector location. The second key needed for calculation of the detector rate is the cross section of the neutron interaction with the detector material and detector response (or just a combined probability of PMT signal per incident neutron).

The calculation of the neutron yield in electron-nuclei interaction is well developed at JLab. Two common applications of the radiation analysis at JLab are radiation protection (control) and detector counting rates. Only at very high luminosity does the neutron induced damage of electronics become important, such as in the recent PREX experiment in Hall A.

1.1 Detector shielding hut of HRS

As an example of our expertise in calculation of the neutron induced rate we recount below the design of the HRS shielding hut. The detector rate induced by neutrons was analyzed by us for the design of the HRS detector shielding hut in 1994-95. The original design of the shielding hut called for very thick walls and twisted labyrinths for cables. That design was used for the HMS spectrometer in Hall C, which was on the fast-track for construction. Because of the large size of the HRS hut (to accommodate the large movable detector frame with electronics), the weight of the original shielding hut was above 1000 tons. Our analysis took into account neutron interaction with detectors and detector response. Analysis was based on GEANT3 with a custom event generator and empirical data for the neutron flux produced by an electron beam in a nuclear target. We demonstrated the possibility of cutting the thickness of the hut walls by more than half. A

GEANT simulation allowed us to take into account the origin of the flux at the target, and the interaction of neutrons with the hall walls and the roof. In the framework of GEANT we took into account the features of the detector response to the neutron interaction, e.g. a Birk correction. This project results in balancing the shielding on different sides of the hut and minimizing the weight for the acceptable counting rate of the detectors. The constructed shielding hut was found to be sufficient (detector rates are always defined by the intensity of the charged particles which pass through the spectrometer) and provided sufficient reduction of the neutron flux (by a factor of 20) to protect the electronics and DAQ components.

1.2 Neutron yield estimate and DINREG

The differential cross section for the electro-production of hadron h can be calculated using the Weizsäcker-Williams approximation (WW):

$$\frac{d\sigma_{e,h}}{d\Omega_h} = \Gamma \cdot \frac{d\sigma_{\gamma,h}}{d\Omega_h},$$

where Γ is the virtual photon flux factor, given by: $\Gamma \approx 0.015 + t/2$, t is the target thickness in units of radiation length, and $\frac{d\sigma_{\gamma,h}}{d\Omega_h}$ is the cross section for hadron production by a real photon. For photon energy below 140 MeV, which corresponds to a dominant part of the neutron yield and is most important for the open detector rate analysis, the neutron photo production cross section is very well known, see `http://www-nds.iaea.org/photonuclear/`. The classic example is the deuteron photo disintegration cross section, which has a wide peak with a maximum of 2.5 mb at photon energy of 4.5 MeV, see Fig. 1. Let us make a complete calculation for an example of a 100 μA electron beam incident on a 5 cm long liquid deuterium target. Such a target has a thickness of 0.85 g/cm^2 or about 0.66% radiation length or 2.5×10^{23} deuterons/cm^2. The effective photon flux is $0.018 \times J_e \approx 1.1 \times 10^{13}$ photons/sec. The total yield of neutrons for photons below the pion threshold could be estimated of 7×10^9 per second.

For careful calculation of the radiation dose, P. Degtyarenko developed a code "DINREG" based on the WW approximation and experimental data of the total and differential photo absorption cross section. The resulting yields of different particles were found to be in good agreement with experiments and have become the gold standard for the background calculations (soft part of the spectra).

1.3 Neutron yield estimation for He-3 target

Calculations of the neutron flux produced in the target cell of the E02-013 experiment are shown in Fig. 2. The target has 43 mg/cm^2 of ^{3}He and 72 mg/cm^2 of GE180 glass. As expected, the low energy neutrons have an almost isotropic distribution. For 100 μA beam intensity, the total neutron production intensity is about 6×10^8 per second, which is 2/3 of the estimation above for the deuteron target at equal target mass. This agreement

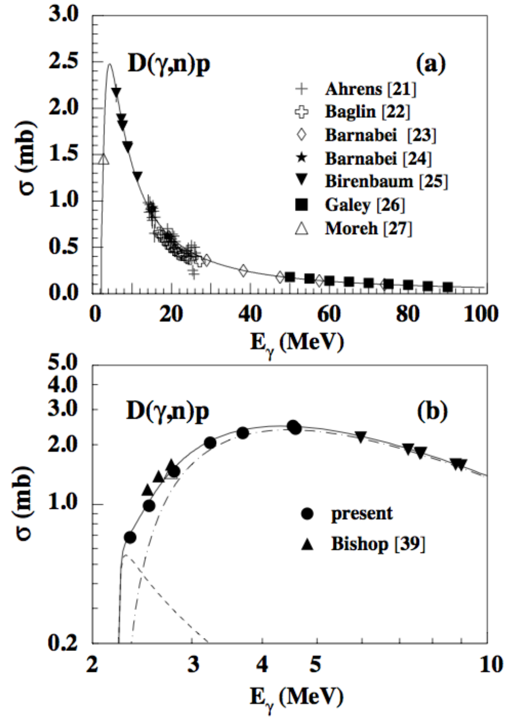


Figure 1: The deuteron photo disintegration cross section.

is very good considering the lower disintegration threshold for the deuteron. A similar estimation of the neutron yield in the Transversity experiment (total material mass on the beam pass of 310 mg/cm^2) and a 12 μA beam current is of 2×10^8 neutrons/second. A full MC simulation for Transversity, performed by V. Nelyubin, gave the larger value for the total neutron flux of 1.2×10^9 per second.

1.4 Neutron detection in PMT glass

For neutron energy above 10-20 MeV, the interaction of the neutron with matter is characterized by nuclear interaction length which is typically of 100 g/cm^2. However, most of the neutrons have low energy between 0.1 and 3 MeV. There is also a special case of the materials such as a PMT borosilicate glass, which contains an isotope ^{10}B with a huge capture cross section. The resulting cross section is $\propto 1/v$ and equals 1 b at 100 keV of neutron kinetic energy. In the PMT glass there is a small fraction of ^{10}B (1% of atoms), which is still enough to capture all thermal neutrons.

For an upper estimate of the possible rate we will use the full neutron flux as the thermal neutron flux. The probability of a signal in the PMT after thermal neutron capture was investigated recently by the LHC collaboration, see Fig. 3. They found that the probability has a very low value, less than 0.03%. Because of its very large cross section, the

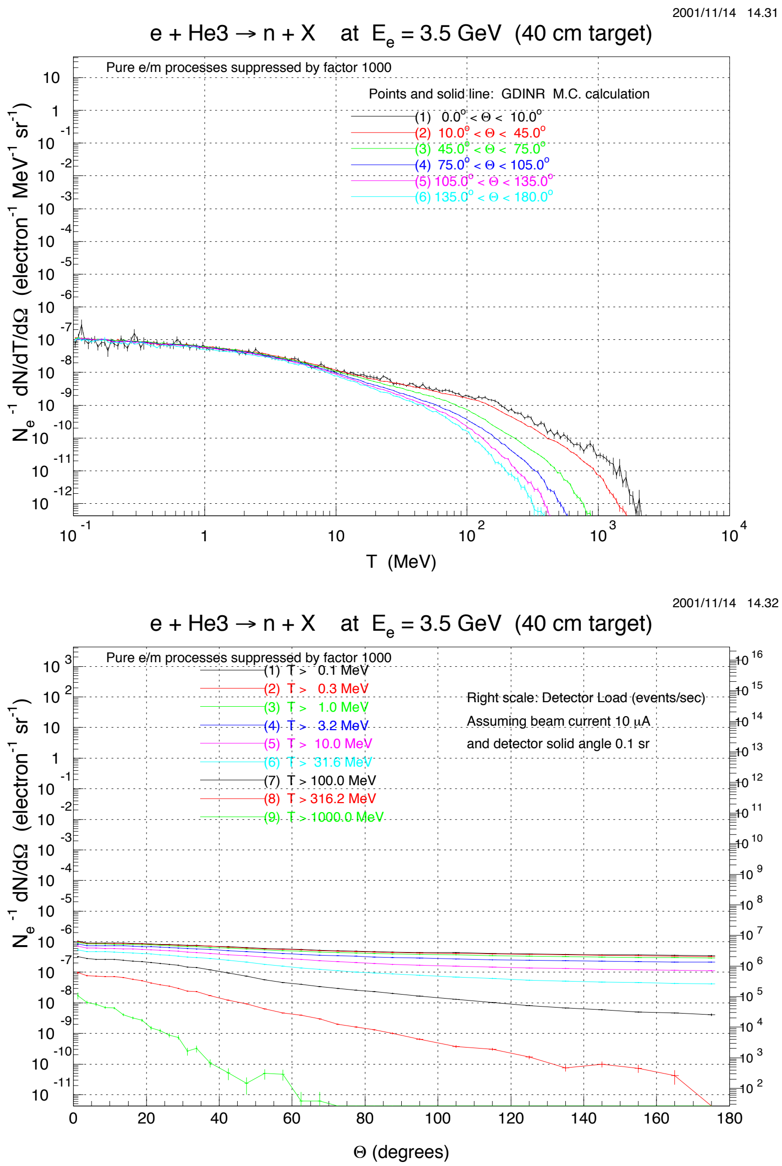
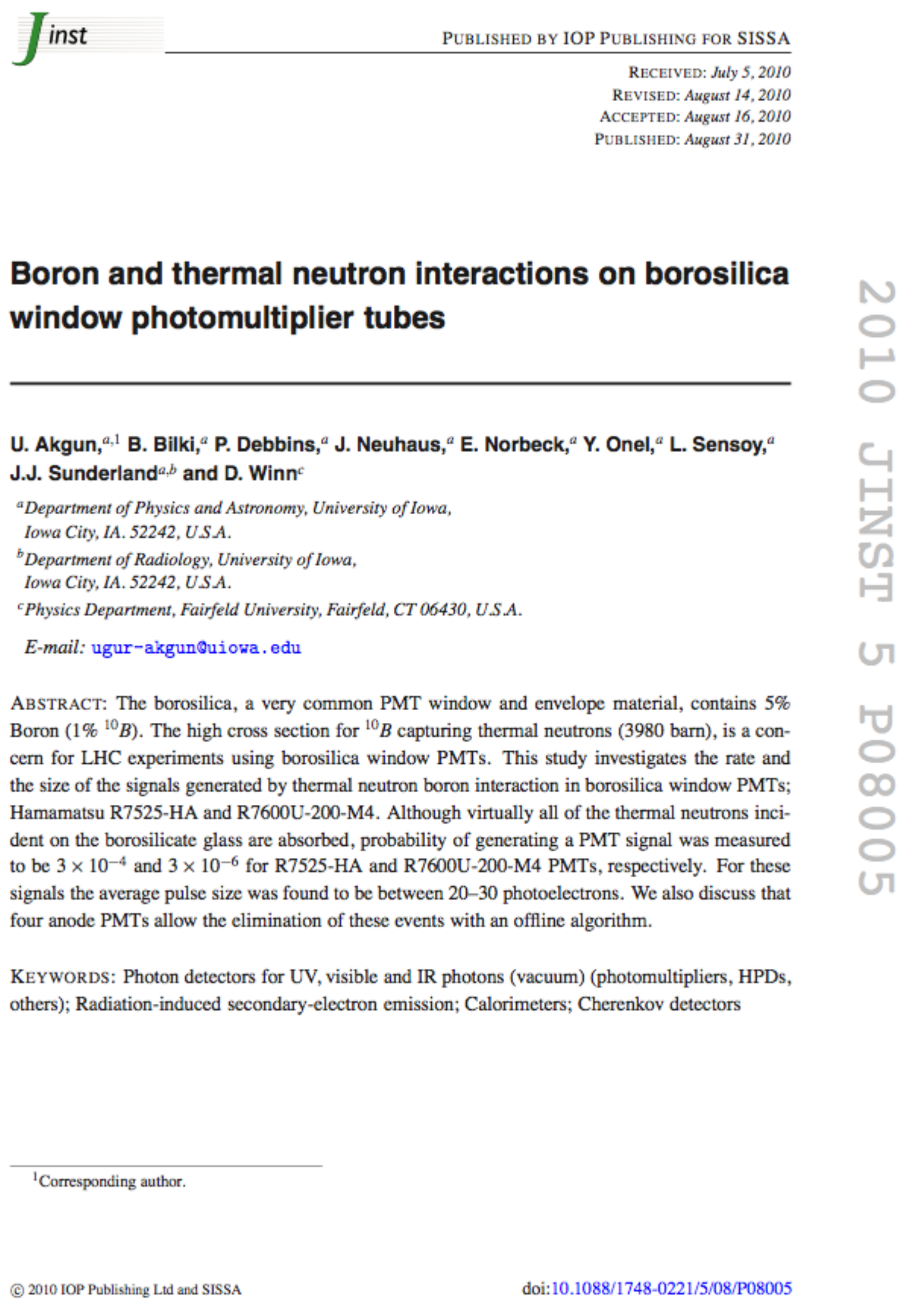


Figure 2: The neutron yield according to P. Degtyarenko's calculation for the E02-013 target and 3.5 GeV beam (only the ^{3}He and the glass cell were included in this calculation).

^{10}B capture dominates, even at a neutron energy of 1 MeV, when the capture probability in a PMT window is about 1-2%. The product of these two probabilities, capture and induced signal in the PMT, drops to the level of 3×10^{-6}. Alternatively, the estimate of the neutron induced rate could be obtained by assuming that neutron interaction with the material is proportional to the PMT window mass in units of nuclear interaction length. In



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Boron and thermal neutron interactions on borosilica window photomultiplier tubes

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ABSTRACT: The borosilica, a very common PMT window and envelope material, contains 5% Boron (1% ^{10}B). The high cross section for ^{10}B capturing thermal neutrons (3980 barn), is a concern for LHC experiments using borosilica window PMTs. This study investigates the rate and the size of the signals generated by thermal neutron boron interaction in borosilica window PMTs; Hamamatsu R7525-HA and R7600U-200-M4. Although virtually all of the thermal neutrons incident on the borosilicate glass are absorbed, probability of generating a PMT signal was measured to be 3×10^{-4} and 3×10^{-6} for R7525-HA and R7600U-200-M4 PMTs, respectively. For these signals the average pulse size was found to be between 20–30 photoelectrons. We also discuss that four anode PMTs allow the elimination of these events with an offline algorithm.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Radiation-induced secondary-electron emission; Calorimeters; Cherenkov detectors

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Figure 3: The front page of the JINST paper on PMT response to the thermal neutron.

the case of a 5” PMT the average thickness of the window is 0.4”, which leads to an estimated interaction probability of 2%. Only a small fraction of interactions (less than 10%)

leads to a PMT signal because a typical path of 8 MeV photon in glass is 10-20 g/cm^2.

Summarizing, we found that the upper estimate of the hit-to-signal ratio is of 0.03% for neutrons with a kinetic energy below 1 MeV and is below 0.2% for higher energy.

1.5 Neutron induced rate in the BigBite Gas Cherenkov

From the size of a PMT (5 inches) and typical distance (300 cm), we can estimate that the fraction of total neutron flux into the window of one PMT is 1.4×10^{-4} or about 1.7×10^5 neutrons/second per PMT. The actual value is less due to the material between the target and the PMTs. The complete MC simulation of the Transversity experiment with the best known geometry provided a lower value of $2 \cdot 10^4$ neutrons/second. By combining this value with the probability of the PMT signal (see above), one can find a PMT rate of a few Hz. An alternative upper estimate leads to a 50 Hz rate. In both cases the rate presents a very small fraction of the actual PMT rate (1-4 MHz), which is likely induced by the low energy electrons and photons (via secondary electron) through Cherenkov light in the PMT glass.

2 Development of the PMT array for RICH

Together with W&M collaborators we are constructing a small RICH counter comprised of 64 PMTs obtained from Ghent University. These PMTs were also part of the HERMES RICH detector. The prototype counter will be used for the study of the rate and front-end-electronics in Hall A during the 2011 and 2012 runs. Through such prototyping we plan to avoid unexpected problems in the actual experiment. The development and testing of the prototype is a usual process of the detector development. It should be not considered as a preliminary check of the PMT rates because a conclusive test of the PMT rates requires an adequate configuration of the beam line and the target.

3 Rate of the PMTs in Gas Cherenkov

The commissioning results of the Gas Cherenkov counter of BigBite are presented in B. Sawatzky's technical note:
`http://www.jlab.org/~brads/d2n/cerenkov/BB_cherenkov-tech_note-v0.5.pdf` Improvement of the GC counter operation as a PID/trigger detector and understanding of the PMT rates are of large interest for all future experiments with this detector.

3.1 PMT response to β particles

Together with UVa collaborators we made a table-top study of the PMT response to the β particles from a Ru-106 source and also a Monte Carlo simulation of that study (see the MC plot of the 100 events). The observed probability of a signal from the PMT was found to be 0.33 for the HERMES 19 mm PMT, 0.40 for a 2” XP2262, and 0.35 for a

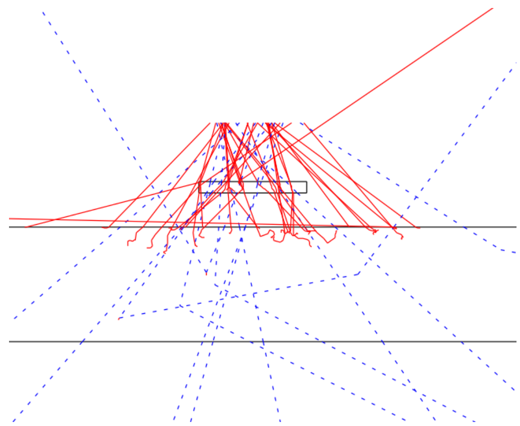

Figure 4: The GEANT display of the electron tracks (red lines) between the Ru-106 source, a scintillator counter (10x10 mm) and the PMT window.

5” XP4572B. The Monte Carlo simulation predicted that in 69% of events, the electron has an energy above 180 keV after it passes through the 1 mm scintillator trigger counter. So, with a probability of 55%, electrons with an energy above the Cherenkov threshold will induce signals in the PMT. Considering that the Ru-106 spectrum has a maximum at 0.7 MeV, such a probability is significant.

3.2 GEANT code for background simulation

A detailed description of the Transversity experiment beam line was realized in the framework of GEANT 3 by V. Nelyubin at UVa. It includes the beam line with the target and the BigBite with all detectors. The counting rate in the front MWDC was found to be 29 MHz, which is close to that observed in the experiment, 36 MHz (corrected on 10% cross-talk between wires). The hit rate of 5” PMTs of the Gas Cherenkov counter for electrons with kinetic energy 180 keV or higher was found to be 1.1 MHz on the small angle side and 0.40 MHz on the large angle side. Assuming a 55% hit-to-signal probability, this leads to values which are less than the average experimental values 3 MHz and 0.3 MHz (see Fig. 5) by factor of 5 and 1.4, respectively.

3.3 Interpretation of the data and the MC results

The observed difference between the rates predicted by GEANT MC and the rates observed in experiment is modest for the front MWDC (a factor of 1.2). However, the difference is large (an average by a factor of 5) for the PMT located on the small angle side of the BigBite Gas Cherenkov counter.

There are several possible effects which could be responsible for the high rate on one side, some of which we listed below in order of their likelihood:
1) the extra background from the beam line which is less important for the front MWDC located closer to the target. Much better agreement for the large angle side PMTs is also

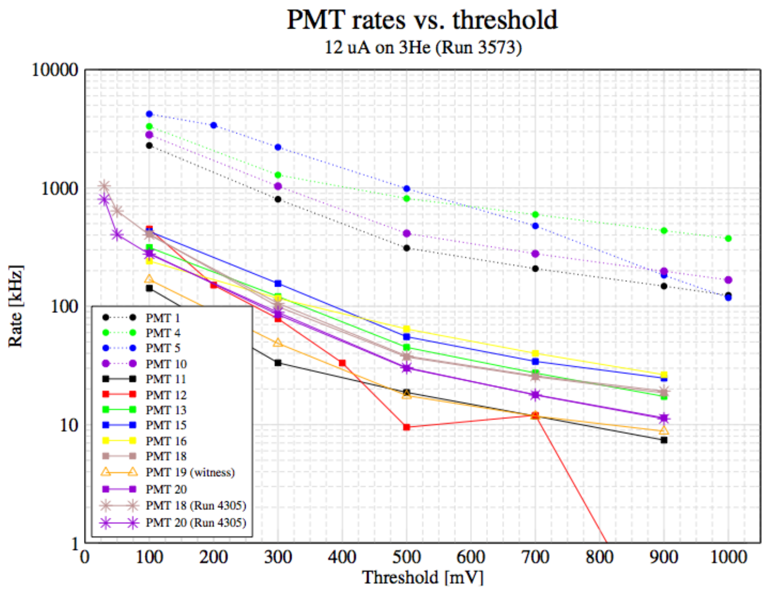

Figure 15: Background rates *vs.* discriminator threshold in the Cerenkov PMTs for 12 μA on the ^{3}He target during Transversity (BigBite at 30°). Gains were matched so that the 1 p.e. signal had an amplitude of roughly 50 mV PMTs 1–10 run from top to bottom nearest the beamline. PMTs 11–20 run from top to bottom on the far (RHRS) side of the BigBite stack.

Figure 5: The PMT rates per B. Sawatsky's report.

indicated on the location of the background source near the beam line side;
2) the after-pulsing of the PMT signal due to the helium gas diffused into the PMT vacuum tube.

4 Summary

GEANT prediction is good to a factor of 1.2 for the MWDC rate and to a factor of 1.5 for the PMT rate. Improvement of the polarized target geometry and the beam line is the most important way to reduce the PMT rates in BigBite. Such improvement includes:
1) a vacuum beam line for the polarized target 2) a lead shielding around the beam line from the point where the scattering chamber connected to the narrow beam line to the dump. The shield extends at least a few meters beyond the end of the detector package.

In view of the observed differences between MC and measurement for the small angle side of the Gas Cherenkov, we will apply an extra factor of 5 to the predicted rate in the BigBite Gas Cherenkov counter which we plan to use in the SIDIS experiment. The possibility that neutrons are a source of extra counting rate in the PMTs of Gas Cherenkov counter of BigBite is ruled out.