Configuration and calibration of the BigBite spectrometer

M. Mihovilovič, for the E05-102 and Hall A Collaborations

Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia

Abstract. Optical calibration of the BigBite spectrometer for the E05-102 experiment at Jefferson lab has been performed. In this paper properties of the BigBite spectrometer and its detector package will be described. Basic ideas and techniques for optical calibration will be explained. For the reconstruction of the BigBite target variables transport-matrix formalism has been considered. The process of calibration is explained in details, together with the latest results. σ-resolutions of the reconstruction are 1.2 cm for vertex position, 11 mrad for in-plane angle and 17 mrad for out-of-plane angle. Robustness of the calibration algorithm has also been investigated. Results of the Scintillation plane gain matching will be shown. Precise calibration of this detector is crucial for particle-identification and energy determination.

Keywords: Physics; Magnetic spectrometer; Magneto-optics; Optical calibration
PACS: 28.41.Rc; 29.30.Aj; 41.85.-p

INTRODUCTION

The E05-102 experiment in Jefferson Lab's Hall A studied the $^3\vec{\mathrm{He}}\,(\vec{e},e'd)$ and $^3\vec{\mathrm{He}}\,(\vec{e},e'p)$ reactions in the quasi-elastic region. The purpose of the experiment was to use Faddeev calculations of the three-body system to better understand the effects of S'- and D-state contributions to the ^{3}He ground-state wave-functions [1]. The beam-target asymmetries $\mathrm{A_x}$ and $\mathrm{A_z}$ were measured in the range of the recoil momenta from 0 to approximately 200 MeV/c. In the experiment a 60% polarized ^{3}He target was used in conjunction with polarized 2 GeV electron beam. The scattered electrons were detected with the High-Resolution Spectrometer [2] in coincidence with the deuterons and protons in the large-acceptance spectrometer BigBite [3]. For that a good calibration of the BigBite detector package is required. Precise understanding of its optical properties is also required.

TABLE 1. BigBite characteristics

Configuration	Single Dipole
Momentum range	$(200-900)\,\frac{\mathrm{MeV}}{\mathrm{c}}$
Momentum acceptance	$-0.6 \leq \frac{\delta \mathrm{p}}{\mathrm{p}} \leq 0.8$
Angular acceptance	96 msr
Flight path*	≈ 3 m
Maximum field	0.92 T
Maximum current	518 A

*during experiment E05-102

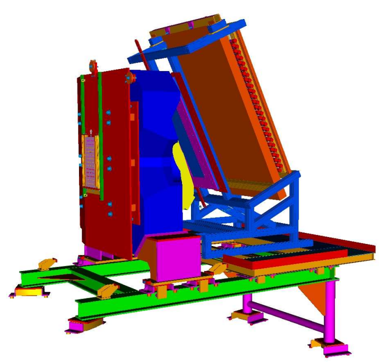

FIGURE 1. BigBite Spectrometer

BIGBITE SPECTROMETER

BigBite is a non-focusing spectrometer with large momentum and angular acceptance (see table 1). It consists of a singe normal-conducting clam-shell dipole magnet, followed by the detector package. In the E05-102 experiment it was used with the hadron detector package, which consists of two Multi-Wire-Drift-Chambers (MWDC) for tracking and a scintillation detector for particle identification.

OPTICAL CALIBRATION

The idea of optics calibration is to determine target variables that have physical meaning from the detector variables that can be directly measured. In BigBite two position coordinates ($\mathrm{x_{det}}$ and $\mathrm{y_{det}}$) and two angles (θ_{det} and ϕ_{det}) are measured. Using this information vertex position y_{Tg}, in-plane and out-of-plane scattering angles, ϕ_{Tg} and θ_{Tg}, and relative particle momentum δ_{Tg} are reconstructed. This can be done in many different ways. For the BigBite various analytical models have been implemented. The simplest one is the effective plane approach. The position of this plane and its inclination depend on the experimental setup and the magnitude of the magnetic field. A bit more sophisticated analytical model is the circular-arc approximation. In this approach an arc of a particle traveling through the magnet is calculated via extrapolation of a track through detectors and the distance of the magnet relative to the target. From the radius of the arc and the density of the magnetic field, the momentum of the particle can be directly calculated, using the Lorentz equation. Unfortunately none of the considered analytical models consider fringe fields at the entrance and exit face of the magnet, which affect the resolution. In addition, the parameters used in these models need to be precisely known in order for the model to work.

Therefore a different approach has been considered, using the transport matrix formalism. Here a matrix is determined which transforms the detector variables directly to the target variables. Various parameterizations are possible. A polynomial expansion of the form

$$\Omega_{Tg} = \sum_{i,j,k} \theta_{det}^{i} y_{det}^{j} \phi_{det}^{k} \sum_{l=0}^{7} a_{ijkl}^{\Omega_{Tg}} x_{det}^{l}\,, \qquad \Omega_{Tg} \in \left\{ \delta_{Tg}, \theta_{Tg}, \phi_{Tg}, y_{Tg} \right\}\,. \tag{1}$$

has been considered since the code for it has already been written and used for the parameterization of target variables in the High-Resolution Spectrometers. Knowing the optics of the spectrometer means knowing the parameters a_{ijkl} and being aware of the limits where such a parameterization works. The polynomial expansion is easy to handle, but one must precisely understand the contribution of the high-order terms. Uncontrolled behavior of these terms can cause wild oscillations of the reconstructed variables, especially on the edges of the acceptance. Our goal is therefore to find a well working low-order optical matrix that has as few high-order terms as possible.

For the precise determination of the matrix elements a_{ijkl}, various calibration measurements were made during the E05-102 experiment. y_{Tg} was calibrated using quasi-elastic carbon data taken with a 7-foil optics target. The position of the foils with respect to the spectrometer are well known and that enables precise determination of the coresponding matrix elements. For the calibration of θ_{Tg} and ϕ_{Tg} we considered carbon and deuterium measurements with a sieve-slit in front of the BigBite magnet and tried to reconstruct all visible sieve-holes. In addition hydrogen elastic data were used for the absolute positioning of the sieve-slit with respect to the optical axis of BigBite, which can not be determined directly from the quasi-elastic carbon data. Finally the determination of the matrix elements for δ_{Tg} is being done by using missing mass peak reconstruction. For that hydrogen and deuterium data are being considered.

The optical calibration began with a manual determination of the low-order matrix elements by comparing various BigBite detector plots to the target plots determined from the HRS-L data. This comparison was possible because only coincidence events in BigBite and HRS-L are being used. The resolution of those results was too poor for further analysis. However, since low-order terms are very robust, they were used to check the convergence of the following more sophisticated methods. After this initial step, an automated method was developed, which considers also higher-order terms and gives results that can be used in a physical analysis. This approach considers up to fifth order matrix elements. The relevant terms for each target variable were chosen using a combination of a Monte-Carlo simulation of BigBite optics and manual selection. The determined set of accepted matrix elements is not unique. Other sets could exist that would give same or even better calibration result. However, it is impossible to know which set is the optimal one. To calculate matrix elements a χ^2-minimization written in Matlab was used. In this algorithm calculated target variables (1) were compared with the directly measured values

$$\chi^2\left(a_i^{\Omega_{Tg}}\right) = \sqrt{\left(\Omega_{\mathrm{Tg}}^{\mathrm{True}} - \Omega_{\mathrm{Tg}}^{\mathrm{Optics}}\left(x_{det}, y_{det}, \theta_{det}, \phi_{det}; a_i^{\Omega_{Tg}}\right)\right)^2}\,. \tag{2}$$

The use of approximately 30 matrix elements for each target variable means that a global minimum in a thirtyone-dimensional space must be found. Numerically this is a very complex problem and it is not certain that the minimization method will not stop in one of the possible local minima instead of the global minimum. Therefore a robustness of the method needs to be examined. This has been done by checking the convergence of the minimization algorithm for a large number of a randomly chosen initial sets of parameters. See Figure 2 for test results for y_{Tg}.

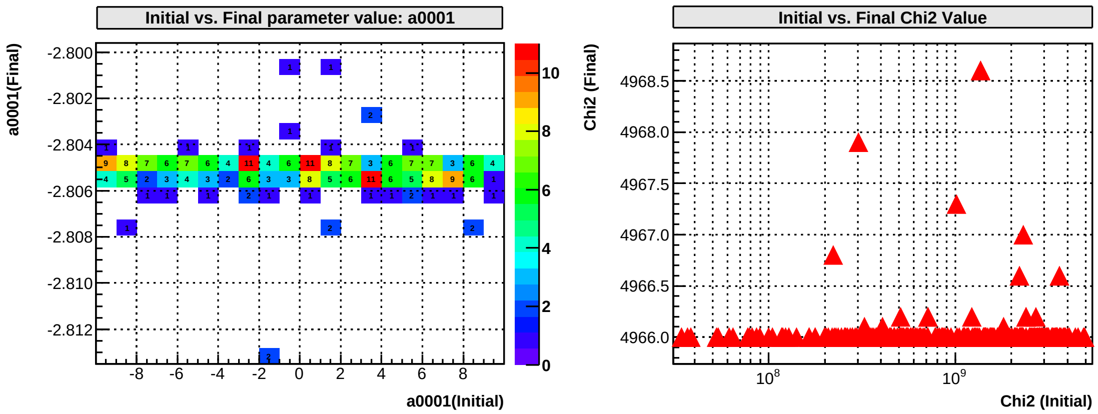

FIGURE 2. Transport matrix element a_{0001} and χ^2-function before and after minimization. The analysis was done for 250 initial randomly chosen points. The fact that vast majority of the initial conditions converge to the same location is an indication of the robustness of the method.

It shows the value of the matrix element $a_{0001} = \langle \phi_{Fp} | \phi_{Tg} \rangle$ before and after the minimization. In the beginning matrix element is uniformly distributed on $[-10, 10]$, while in the end it is normally distributed around the value of -2.81. The final value of the χ^2 function is more than four orders of magnitude smaller than before the minimization.

The results of the optical calibration for y_{Tg}, θ_{Tg} and ϕ_{Tg} are summarized in Table 2. A comparison with the NIKHEF calibration results, where BigBite was used with a different detector package as an electron spectrometer, before its arrival to Jefferson Lab, are also presented. It is shown that NIKHEF resolution was for a factor two better. This deterioration of the resolution has been expected since BigBite is now used for hadron detection instead of electrons, with different detector package. The determination of the matrix elements for δ_{Tg} is still in progress. For the precise missing mass peak reconstruction a well-working particle identification (PID) is required to distinguish quasi-elastic protons from elastic deuterons in ^{2}H calibration data. Therefore the behavior of scintillation detectors needed to be understood before δ_{Tg} determination could be preformed. Now that scintillation detector calibration is done, the determination of δ_{Tg} matrix elements should be done quickly.

TABLE 2. Resolution of BigBite optical calibration and comparison with NIKHEF results.

Target variable	E05-102 calibration	NIKHEF*
$\sigma(y_{Tg})$	1.1 cm	$(0.3-0.8)$ cm†
$\sigma(\theta_{Tg})$	17 mrad	$(3-6)$ mrad
$\sigma(\phi_{Tg})$	11 mrad	$(3-6)$ mrad
$\sigma(\delta_{Tg})$	Not calibrated	0.8%

* BigBite used as electron spectrometer with different detector package
† depending on the energy of e^-

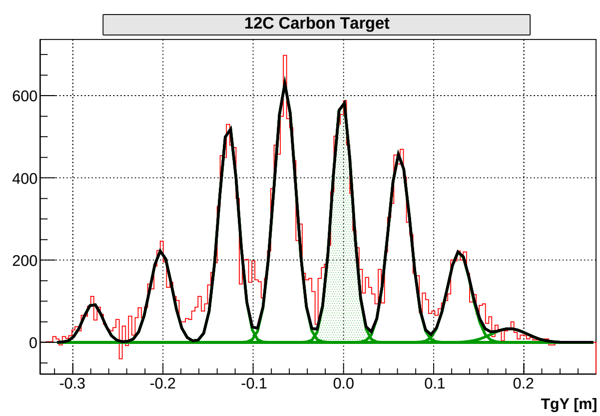

FIGURE 3. Reconstructed vertex position

SCINTILLATION PLANE CALIBRATION

The BigBite scintillation detector is made of two segmented scintillation planes, a thin 3 mm dE-plane and a thick 3 cm E-plane. Each plane is 2 m long and is made of 24 equal scintillation paddles. The signal from each paddle is read by two photo-multiplier-tubes mounted on each end of a scintillation bar. The calibration of this detector therefore means matching gains on each of the 96 PMTs. First gain matching was done before the experiment where actual high voltages on PMTs were properly set using cosmic rays. This is important for the correct discrimination of the signals and proper work of the trigger circuit. Unfortunately this calibration is only approximate, because precise calibration with low-rate cosmics was not possible due to strict time constraints. Final calibration was therefore done after the experiment by introduction of the correction factors in the analysis software. For this real production data on various targets were used. The calibration has been done in two steps. First we gain-matched signals from the two PMTs mounted on each scintillation paddle. Here light output attenuation effects along each bar have also been considered. In the final step signals from neighboring paddles have been compared and properly adjusted. The end effect of this calibration is shown in Figure 4. Deuterons with momenta between 340 $\frac{\mathrm{MeV}}{\mathrm{c}}$ and 580 $\frac{\mathrm{MeV}}{\mathrm{c}}$ can now be well identified and separated from protons. This is of crucial importance for the success of the E05-102 experiment.

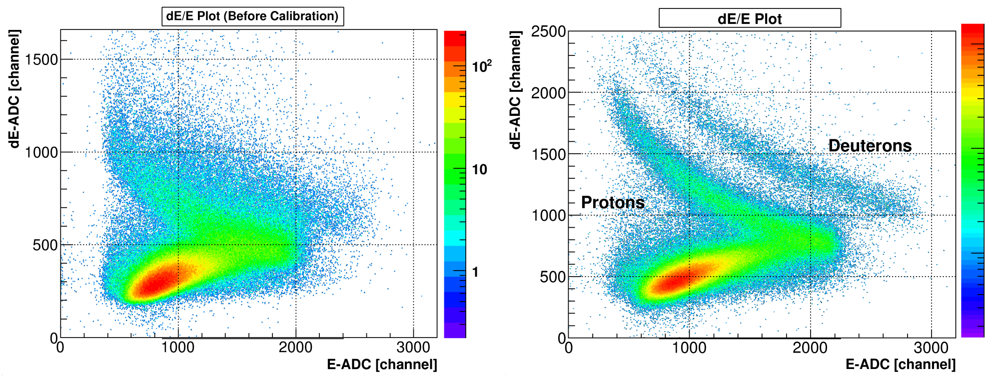

FIGURE 4. Energy deposition in dE and E scintillation planes before and after the calibration. After the process of gain matching deuterons can be well separated from protons.

CONCLUSION AND OUTLOOK

During the optical calibration of the BigBite we learned that use of analytical models is not very promising, mostly due to the fringe-field problems and ambiguities in the input parameters required by the model. Transport matrix formalism gives better results. A matrix with low-order terms is preferred, since higher order terms can cause oscillations on the edges of the acceptance. The described calibration method already gives nice results for y_{Tg}, θ_{Tg} and $\phi_{T}g$. The analysis for δ_{Tg} is underway and will hopefully be done soon. The calibration of the BigBite scintillation detector has also been considered. ADC signals from all PMTs have been properly gain-matched and can now be used for particle identification as well as for the estimation of the particle momentum via the energy deposition in the bars using the Bethe-Bloch equation [4]. Another option for the particle identification and energy determination is through the time-of-flight measurement using the TDC information. The analysis of these signals will be done in the next step of calibration. However, when all parts of the calibration are finished, precise information on particle momentum and its identity could be obtained via three independent techniques.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of Energy and the U.S. National Science Foundation. It is supported by DOE contract DE-AC05-06OR23177, under which Jefferson Science Associates, LLC, operates the Thomas Jefferson National Accelerator Facility.

REFERENCES

1. *Measurement of A_x and A_z asymmetries in the quasi-elastic* $^3\vec{\mathrm{He}}\,(\vec{e},e'd)$, S. Širca, S. Gilad, D. W. Higinbotham, W. Korsch, B. E. Norum (spokespersons), JLab Experiment E05-102, June 2005
2. J. Alcorn *et. al.*, Nucl. Instr. and Meth. **A 522** (2004) 294
3. D.J.J. Lange *et. al.*, Nucl. Instr. and Meth. **A 406** (1998) 182
4. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag, Heidelberg, 1987.