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– INSTITUTE OF PHYSICS AND ASTRONOMY

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Sub: Evaluation of PhD dissertation submitted by Gábor Nyitrai

This review summarizes my evaluation regarding the thesis titled "Particle Physics Detector Development and Application for Muograqphy" authored by Gábor Nyitrai. This thesis demonstrated a critical contribution to the field of muography, an emerging field for various interdisciplinarity studies (e.g. geography, archaeology) based on detector technology developed originally for experimental particle and nuclear physics. I read this thesis with joy and found the components studied by the author are very comprehensive including several outstanding contributions to the development of muography technologies.

There are four key statements in the thesis: 1. MWPC detector design and construction, which is the author's choice of detector technology among other techniques available in the field, 2. Low gas consumption, which requires stricter requirements for field applications compared to usual lab-based experiments, 3. GEM-based detector for UV detection, which I found not only useful for Cherenkov light detection but also other applications (thus let me discuss later in this report), and 4. Muographic data analysis, which demonstrates the physics capability of the author's approach. Through these key studies, the author demonstrated key knowledge of the field including detector development and construction, problem-solving ability towards the goal of the research theme, leading contribution to field activity for data collection, and interpretation of collected data through analysis procedure. All these features are conducted with very high standards. In particular, I found that the state-of-the-art detector development aspect is outstanding in the field of gaseous MPGD. In the following, I will give my evaluation of each key statement, but first **I clearly state that the thesis is very well-formulated as a scientific document, thus I consider that the work should be rewarded with a PhD degree in the case of a successful defense.**

On the MWPC detector design and construction, the author investigated the application of an innovative MWPC technology called the Close Cathode Chamber (CCC) for muography. The author demonstrated their own significant contribution to the detector construction and gave sufficient details on how to overcome emerging difficulties. Descriptions of, for instance, Section 3.1.1 are given comprehensively based on the author's direct experience, and it is certainly considered an achievement led by the author. As an additional note, I found one place where the additional drawing could be shown. Figure 3.3 and the associated main text in Section 3.1 explain the Data Acquisition (DAQ) system. Although the author did a good job explaining the system in sentences, adding a data flowchart drawing would give more supplemental information for readers to easily catch up with the overall picture of the system. This could

be a consideration on how to improve the presentation of the thesis. Nevertheless, I note that this suggestion is minor, and the scientific value of this PhD dissertation is unchanged without such a flowchart drawing.

On the Low gas consumption, the author clearly stated the requirement of the detector and comprehensive R&D activities made. I have experience in the development and construction of a gaseous TPC for a high energy experiment application. Therefore, I understand that reduction of consumption while keeping the gas quality sufficiently high is a very challenging topic. The author extensively studied the typical concerns on gaseous particle detectors and demonstrated that required gas quality in terms of signal gain has been achieved for long-term operation with low consumption. One such example appears in Figure 3.17. I was impressed by how deeply the author investigated achieving low gas consumption operations for the field application, and it must be highly appreciated by the community.

On the GEM-based detector for UV detection, the author conducted a dedicated study to address the gain homogeneity of the ThickGEM+CCC (TCPD) detector. It is worth noting that charge and photon simultaneous detection is an emerging demand that the recent high energy physics wants to have. For instance, it could be an innovation for the gaseous TPC if the detector is capable of measuring not only drifted electrons (particle track reconstruction) but also a UV scintillation photon (timing determination, or so-called T0 determination). The author's primary goal is to apply TCPD for Cherenkov light detection, but I would stress that this R&D could be innovative beyond the scope of this thesis. I found that this R&D is thus outstanding and the author's extensive study on the basic properties of the detector (for instance, Figure 3.38 on photoelectron response) is invaluable.

In the Muographic data analysis, the author provides enough details necessary to follow the analysis procedure. Starting from the necessary input parameters (e.g. cosmic muon flux models) it clearly explains the creation of muographic image production from raw data. I found one thing a bit unfortunate **the impact of systematic uncertainty on the final results** is hard to extract from the given results, although systematic uncertainty sources are extensively explained in Section 4.1.3. For instance, the author explains a case study of underground muography in the Királylaki tunnel. There are lots of interesting results shown with good visualization (e.g. colorful figures in Figure 4.13 and 4.14), which confirm the very important results. However, these styles of figures typically make it hard to extract the impact of systematic uncertainties on measurements, thus it would be nice if one could consider somehow demonstrating another way to present the impact of systematic uncertainty in the analysis. On the same aspect, Figure 4.16 includes error bars on measured points, but it seems less clear which sources are included/dominant (thus I will ask later). But let me stress that this is a suggestion for future improvement. I do not have any objection regarding the significance of the scientific achievement of the study, and I am fully appreciative of the author's significant contribution to the field.

Based on the above-mentioned evaluation, I consider that this thesis is written to a very high standard and, thus must be considered for public assessment through the defense procedure. I have 2 questions that I want to make sure of relating to the author's contribution to muographic data analysis, as well as a question I want to discuss given an excellent opportunity for me to discuss with a gaseous detector expert for future application. These are as follows:

1. From page 16, the author discusses four major background cases. **Which one of the four background categories was the most concerning contribution to your measurement?** And **what will be your suggestion for the next project to improve that situation?**

2. From page 87, a case study is shown and results are presented in multiple figures. **Could you comment in more detail regarding your systematic uncertainty on this case study about Section 4.1.3?** For instance, I could not follow well which systematic uncertainty sources ended up with the dominant (or negligible), as well as how large the statistical uncertainty on the measurement was.

3. From page 57, a novel detector development that combines Thick GEM and CCC (TCPD) is given. To me, it seems a huge potential in addition to the author's primary goal for the detection of Cherenkov light. For instance, it will be very beneficial for future TPC applications to simultaneously detect electron drift charge and primary scintillation UV photons. Many experiments in high energy physics (e.g. neutrino physics, dark matter search) seek simultaneous detection of charge and photon particularly under the high-pressure environment (to maximize gas density or number of target nuclei). I understood from the author's description, for instance, Section 3.1 regarding the mechanical strength of CCC technology and I can imagine that it could be mechanically stronger under over-pressure operation, but an expert's opinion will be very valuable here. **Do you have any concerns (or see any benefits) about TCPD technology application under an over-pressure environment (let's say 2-10 bar)?**

(Question #3 is intended to consult with an expert who actually developed a novel MPGD detector. Feel free to comment with any thoughts and I would appreciate on any information coming out.)

Given a very clear and detailed explanation in the PhD dissertation written by Mr. Gábor Nyitrai, I consider the results and works presented to be fully conducted with his tremendous effort. Therefore, **I accept them as new scientific results given by him.** This thesis is written with comprehensive information regarding the field of muography as well as his own approach with sufficient details. I found the structure of the thesis to be very proper as a form of scientific presentation to be considered as a PhD candidate. Therefore, **I recommend his work on muography for public defense.**

Sincerely,

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