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**Report on the doctoral dissertation thesis „TACTIC: The TRIUMF Annular Chamber for Tracking and Identification of Charged Particles" by Lars MARTIN**

The thesis under evaluation here reports on the characterization of the TACTIC time projection chamber that is under development for the TRIUMF radioactive ion beam facility in Vancouver, Canada. The candidate uses experiments with an $\alpha$-particle source and Monte Carlo simulations to this end.

In a brief first section, the astrophysical motivation for the development of the TACTIC detector is outlined, focusing on the $^{8}$Li($\alpha$,n)$^{11}$B reaction that plays a role in inhomogeneous Big Bang scenarios and in selected scenarios for the astrophysical r-process involving light, neutron-rich nuclei. In addition, a literature review of previous experimental efforts on this nuclear reaction is given, focusing on the detection apparata used. The use of an active target time projection chamber such as TACTIC is motivated.

The second section concentrates on the physics of ion chambers, in particular time projection chambers (TPCs). Data from the well-known SRIM software are used for the energy loss, but for the (angular and energy) straggling a semi-empirical formula is used instead. Based also on the literature review from the previous section, an instructive overview of recently built TPCs used for nuclear physics purposes is given. The gas-electron multiplier (GEM) foils used as first amplification stage are also discussed, but it is not clear why the effective GEM gain in the TACTIC setup is just 10, instead of $10^2$-$10^4$ as reported in the literature.

In the third section, the setup of the TACTIC detector is described in detail. The complex geometry and the signal generation and amplification are explained exhaustively, using instructive graphics and detailed tables that serve for the later analysis.

The fourth section is devoted to Monte Carlo simulations. The candidate addresses the well-known problems of the Geant4 simulation package with low-energy ions by some special adjustments of the code. Unfortunately the comparisons between Geant4 and SRIM are only shown for the original Geant4 code, without the new adjustments, so the reader is left to hope the corrections applied really help. For describing the electron drift, the specialized software package Garfield is used instead of Geant4.



A brief fifth section describes the data acquisition system used.

The core of the thesis lies in sections 6 and 7, which make up well over half the volume of the thesis. Section 6 describes the data analysis software developed by the candidate. Considerable effort is devoted to quantifying and explaining the uncertainties of the estimated radii and angles. Practical working formulae are developed and justified. The crucial tracking algorithm is tested against a Geant4 simulation, showing impressive theoretical performance. A useful alternative second way to derive the track angle, using only the first point, is developed and discussed for problematic cases. It is not clear to me whether a slight modification using only 2-3 points might also offer some benefits for situations with a distributed source.

Section 7 is devoted to the analysis of data taken with $\alpha$ sources, most notably a $^{148}$Gd source which provides a challenging test case with just 3.2 MeV $\alpha$ energy. Great effort is spent on discussing and mainly solving synchronization issues evident in some runs. The noise rate, which is of decisive importance for a low counting rate nuclear astrophysics experiment, is shown to be low enough not to limit data taking, except for some cases with defective data acquisition. Even the radioactive background from $\alpha$-emitters intrinsic to the detector is studied, and Bragg curves are shown to demonstrate the physical nature of this particular background. The actual measured distances between the calculated track and the measured individual point positions are used to quantify the precision of determining point coordinates.

The data acquisition (DAQ) modules used a built-in algorithm to derive time and amplitude information from the signal waveform. Using data where also the waveforms were recorded, the candidate checks this algorithm and discusses in detail some problematic cases. The saturation rate of the DAQ is measured. The detailed geometrical considerations in sections 3 and 6 are impressively borne out by the $\alpha$-source data. The tracks that are reconstructed in physically inaccessible parts of the detector are used to understand the uncertainties inherent in the tracking algorithm. It is shown that these problems can be addressed by relatively simple analysis cuts. The tracks are then used to determine the position of the $\alpha$ source in the offline analysis, showing some eccentricity that is well within experimental parameters.

The TACTIC detector is then used to re-determine the activity of the $^{148}$Gd source used, finding values that are in good agreement with measurements with standard techniques, except for one case where one is left to question whether the source position was correctly transcribed. The detector is shown to exhibit some warming-up effects that affect the results in the first few minutes of operation, but for long nuclear astrophysics beam times this problem should not present an obstacle. An unfortunate heterogeneity of the amplification factor by channel is found and discussed in detail. It is not clear to me whether this is due to variations in the (overall very low) GEM yield or due to deficiencies in electrical signal transmission and amplification. However, the candidate solves this issue by showing that the track length (for stopped tracks) gives a very precise estimate of the deposited energy, i.e. for stopped tracks the inhomogeneities do not affect the analysis. Finally, it is briefly discussed how additional observables from the

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DAQ firmware analysis of the waveforms might enhance the precision in the future.

The data are summarized and discussed in the eighth section. The rate capabilities are compared with competing other TPCs. Unfortunately, the recent upgrade of the RIKEN-based GEM-MSTPC with so-called „thick GEMs" seems to have escaped the candidate's notice (H. Ishiyama *et al.*, J. Inst. 7, C03036 (2012)). With this upgrade, the GEM-MSTPC has a reported rate capability that is competitive with TACTIC. Subsequently, the particle identification capabilities are studied, based on the simulation.

The ninth and final section gives an outlook on the use and possible upgrades of TACTIC.

The thesis is well readable, written in very good scientific English and supported by many instructive viewgraphs. The candidate shows a deep understanding of the physical processes inside the detector he studied and exhaustively analyzes the data he took. After explaining the physical effects, practical formulae are given to quantify many of the processes in the detector, enabling future data analysis. Monte Carlo simulations are used in an appropriate manner to study effects that would otherwise be incomprehensible.

The main strength of the thesis lies in the in-depth study of the detector with experimental observables wherever possible, and in the detailed discussion of all relevant effects. – The main weakness of the thesis is the limitation of its scope to just the TACTIC detector and just the $\alpha$ source data. The candidate offers only cursory glimpses of the science of his mainly aimed for reaction, does not discuss other possible science cases at all, and uses only the Monte Carlo simulation (and not the in-beam test data) to extend his $^{4}$He-based conclusions to ions such as $^{8}$Li and $^{11}$B.

Summarizing, I wholeheartedly recommend to accept this very good thesis as a doctoral dissertation.

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