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**Referee report on doctoral thesis
of Maciej Perkowski
“Precision measurements of the electron energy distribution in nuclear beta decays”**

The doctoral dissertation of Mr. Maciej Perkowski has been completed at the Institute of Physics of FPAACS of the Jagiellonian University (and at the Faculty of Sciences of the Catholic University in Leuven, Belgium). Its subject is a fragment of a broad scientific program conducted by the group from IF UJ and KU Leuven. The research aims at precise measurement of the shape of beta energy spectrum in the range from 100 keV to several MeV. In particular, the goal of the group is to derive the value of the coupling constant present in the description of the weak interaction, which is induced by the strong interaction between quarks in the decaying neutron. This component is called a weak magnetism. In order to effectively deduce the value of the coupling constant relevant to weak magnetism, the energy spectrum of beta decay must be measured with an accuracy of at least 10^{-3} .

If the mentioned accuracy of measurement is achieved, it will permit as well to increase the precision of the currently known limit for a non-zero value of the so-called Fierz term. It is a constant present in the formula for the energy of the beta spectrum. It depends not only on vector and pseudo-vector (axial-vector) coupling constants allowed in the Standard Model but also on the scalar and tensor components of the interaction. Fierz factor is therefore a quantity sensitive for the physics beyond the Standard Model. Its non-zero value would be an indication of the need to extend the description of weak interactions beyond the traditional model (V-A).

Mr. Maciej Perkowski worked on the preparation of experimental and analytical tools allowing for precise registration of the beta spectrum and the deconvolution of studied physical quantities. His thesis is a profound feasibility study of the intended measurements with using a hybrid spectrometer called "miniBeta". The prototype spectrometer consists of a scintillator for measuring the energy of beta particles and a gaseous drift chamber for registration of particle tracks. The task of the latter is to identify and select the events, determine the spatial distribution of events registered in the scintillator, and discriminate the experimental background. Dedicated analogue- and commercial digital electronics are used to readout and process the signals. The data acquisition system, a set of dedicated computer programs which constitute an environment for selection and event analysis, and a graphical user interface complete the prototype experimental system used in the test measurements.

The dissertation consists of eight chapters, one appendix and exhaustive bibliography. It contains large number of carefully prepared figures, which well illustrate the described material. Text is written clearly in good English.

In the introduction to the thesis the general issues related to the planned research and the characteristics of the used experimental system are outlined.

Chapter no 2 provides an introduction to the Standard Model with a brief specification of its applicability limits. Later the Author focuses on the characteristic of weak interaction sector in the Standard Model. He explains in detail the structure of Hamiltonian used for description of beta decays and gives the classification of nuclear beta decays. In the discussion of the interaction term of the Hamiltonian Mr. Perkowski explains the origin of the coupling constant responsible for the so-called weak magnetism and informs about measurement accuracy necessary to notice the influence of this force. Discussing the possible manifestations of interactions which are not considered in the Standard Model, the Author explains in detail the origin of the so-called Fierz term. Its measured non-zero value would be an evidence of the presence of the interference with the scalar and tensor components of interaction. Thus, would confirm the non-zero value of those two components disregarded in the Standard Model.

In the third chapter the PhD Candidate explains the experimental strategy adopted in the conducted research and describes the experimental apparatus foreseen for the measurement. The choice of a plastic scintillator as a material for a beta particle spectrometer is convincingly justified as a compromise between the worse spectroscopic properties of this material compared to other known particle detectors and a much greater likelihood of full energy absorption in a light organic scintillator. The precise measurement of the energy deposited in the scintillator by the beta particles will be supported by information obtained from a position sensitive multi-layer drift chamber of very low effective thickness working as a tracker. The tracker should allow to record and eliminate events, in which the beta particles bounced off the surface of the scintillator (backscattering). Learning about the track orientation will permit as well to suppress the events that do not originate from the tested beta source. The drift chamber provides also information about the location of the particle hit on the surface of the scintillation detector. This will allow the light output calibration and introducing the corrections for the light transport and attenuation in the scintillation material and the light-guide.

In the presentation of the detection system special emphasis was put on optimization of the construction and minimization of the effective thickness of the drift chamber. This detector has to provide the sufficient position resolution and high efficiency when registering the particles tracks. But on the other hand the tracker should only minimally affects the shape of the measured spectrum of beta particles. For these reasons the construction of a drift chamber with hexagonal cells and a honeycomb structure was chosen. This ensures the optimal shaping of the electron drift field and simultaneously the smallest filling of the chamber with electrode wires. A light helium-based gas mixture is used as a detector medium. Additionally – to minimize its effective thickness - detector is operated at underpressure. For the reconstruction of the track position in the axial plane of the detector a traditional method based on the measurement of the drift time of electrons originating from ionization of the medium gas is used. The third coordinate is calculated from the difference of the electric charges collected on both sides of the anode wires (charge division technique). For this purpose the chromium-nickel alloy of high resistance was used for the signal wires. A dedicated readout electronics has been built. It permits both the measurement of the drift time and the amplitude of signals at both ends of the signal wire. The PhD Candidate prepared also the software for supervising the components of the detection system. It enables to control the composition of gas mixture, its flow rate and its pressure. Also the possibility of setting the supply voltages for the chamber and control of the leakage currents together with emergency power off is provided. Other functionalities of the control software are: setting of the data acquisition parameters and the values of discriminator threshold; changing the position of the beta source; measuring and recording the atmospheric pressure and the ambient temperature. Another tools provided by Maciej Perkowski are the user interface facilitating the visualization of

recorded events and a wide set of procedures for detailed data analysis. Software tools prepared by Mr. Perkowski are written in Python programming language.

Very extensive third chapter contains as well a broad and didactically useful summary of basic knowledge on the development of the tracking techniques of charged particles and the operational principles of gaseous detectors, in particular the drift chambers.

The examination of measurement precision of the beta energy spectrum and contributions to systematic uncertainty of this measurement were carried out using a square scintillator with a 100 mm side and a thickness of 10 mm. One photomultiplier tube placed in the scintillator axis was used. Light from the scintillator volume was collected through light-guide. The energy spectra measured for the ^{207}Bi source emitting conversion electrons with well defined spectral lines have been compared to the results of computer simulations made with the help of the GEANT4 package. From this comparison The Author realized a great importance of geometric optimization in the construction of the final spectrometer for beta spectrum measurements. He confirmed as well the need for the careful calibration of the dependence of light output on the position of the hit at the scintillator surface. The Author proposed a universal method of multi-parameter energy calibration of the spectrometer, which allows to determine the energy resolution and to calculate the systematic error of calibration. It is of key importance when measuring the Fierz factor and weak magnetism. Despite that the energy resolution of the prototype spectrometer turned out to be insufficient to carry out the planned measurements with the demanded precision, the PhD Candidate has defined and described the improvements necessary for the construction of the ultimate spectrometer capable to provide the required measurement precision.

A certain lack of dissertation of Mr. Perkowski is too brief description of the prototype of scintillation spectrometer. Information about the material, shape, the type and size of the photomultiplier tube, their interconnection would allow the reader to understand better the problems related to the light measurement in the prototype version of this detector.

A significant part of his work PhD Candidate devoted to a very careful study of the operation and performance of a particle track detector. The results are described in chapters four, five and six of the doctoral dissertation. The difficulty in operation of this detector arise from the fact that on the one hand the detector should have the small effective thickness in order to minimize distortions of the measured energy spectrum. On the other hand the chamber is foreseen to register, with high efficiency and precision, the tracks of beta electrons, thus, particles with relatively low ionization capability of the medium and undergoing significant dispersion. Using a simplified detector consisting of a scintillator and only one layer of the tracker, Mr. Perkowski sought the optimal working point of the chamber. He took into account the composition of the gas mixture, its pressure and the supplied high voltage. The beta source of ^{45}Ca was used. In order to investigate the systematic effects related to signal readout and processing, he performed the measurements using two independent data acquisition systems. The detector behavior was analyzed in detail for various gas mixtures of helium with varying quencher concentration and at different pressures. As a quencher the isobutane has been selected. As an effect of these initial tests the need to filter out of the delayed signals resulting from unwanted ionization effects in gas has been noticed. Extension of the ADC dynamic range and the use of a leading edge discriminator (instead of initially used CFD) for signals from the drift chamber was found to be also a necessary modification. Moreover, the stabilization of the ambient temperature was applied while conducting the further measurements.

The PhD Candidate concluded that with the use of a mixture composed of 50% of helium and 50% of isobutane kept at the pressure of 600 mbar the chamber attains the sufficiently high detection efficiency together with the long term stable operation mode. Mostly for these gas mixture and operating pressure, the detailed tests of the efficiency and resolution with the use of a full detection geometry (tracker consisting of ten layers) were carried out. The high voltages for individual layers were selected individually in order to obtain the similar detection performance and the shape of the energy spectrum from the ^{207}Bi source for the entire detector.

Mr. M. Perkowski describes in detail the principles of the time-position calibration of a cylindrical drift chamber with the use of cosmic rays. This calibration allows the calculation of coordinates of particle track in the "x-y" plane. Taking into account the geometric deviation of the hexagonal drift cell of his chamber from full cylindrical symmetry, he introduces the iterative autocalibration method. The Author defines also a fit quality parameter in order to quantify the improvement in each step of autocalibration algorithm. To increase calibration accuracy, he divides the radius of a drift cell into smaller fragments (nodes), for which he calibrates separately. In this way he calculates the systematic shifts in $r(t)$ distributions for individual drift time ranges and compensate them in subsequent autocalibration steps. The optimal calibration curve ($r-t$) Author obtained after five iterative steps. He achieved demanded symmetrization and minimization of the width of the residua distributions and shift of their mean values to zero.

The PhD Candidate carefully considers the possible systematic contributions to the track position measurement in the miniBeta drift chamber. These are: (1) the "walk effect" resulting from the nature of ionization induced by charged particles in gasses and from the need to use a "Leading Edge" discriminator. In a separate test, the Author measures the dependence of the drift time on the signal amplitude and proposes its analytical parametrization. The latter is used to compensate - almost completely - the "walk effect"; (2) the so-called right-left ambiguity of track matching. The PhD Candidate notes that for certain spatial orientations of the recorded tracks, it is impossible to completely eliminate this effect. Therefore, the tracks of such feature are excluded from calibration procedure; (3) determination of the minimum drift time t_0 . Mr. Perkowski realized the limitation of the autocalibration method for the particle tracks passing at the smallest distances from the anode wires. Therefore, t_0 values for individual drift cells are determined separately taking into account only the tracks passing at a distance of ± 0.5 mm from their centers; (4) finite precision of positioning of signal and field wires. The Author notes a systematic shift of the centers of individual drift cells in the "x" direction. He identifies this effect as displacements of individual detection planes relative to the assumed geometry. This can be caused by the limited mechanical precision of the detector construction and its assembly. For this reason Mr. Perkowski introduced additional steps to the autocalibration procedure. He creates the residua distributions separately for the "x" and "y" coordinates, calculates their average values and performs appropriate compensation in the position of the signal wires; (5) dependence of signal amplitude on the radial position of the track in the drift cell. The Author notes a systematic decrease of signal amplitude for the tracks detected at higher distance from the center of the cell. For the above-mentioned contributions to the calibration uncertainty of $r-t$ dependence, the Author, where it is possible, calculates corrections and values of systematic error.

Using the results of the described above iterative calibration ($r-t$) and applying the obtained corrections PhD Candidate calculated the position resolution and detection efficiency for individual drift cells of the detector. He did it for the cosmic muons registered with the use of various gas mixtures and the

corresponding high voltages. The results are consistent and indicate that the 50/50 mixture of helium and isobutane at a pressure of 600 mbar is optimal from the point of view of detector stability. With this gas composition the accuracy and efficiency of planned measurements will be sufficiently high. The position resolution along the radius of the drift cells varies from 400 to 600 μm and the average efficiency of individual cells is greater than 97%.

To obtain the third spatial component for recorded particle track (the "z" coordinate), Mr. M. Perkowski uses the method of electric charge division along the signal wire. He measures the signal amplitudes at both ends of the signal wires and calculates the position of the track along the wire from the amplitude asymmetry. Also here the PhD Candidate examined the systematic factors affecting the accuracy of the signal amplitude measurement. He measured the offset (pedestal) values of the ADC and calculated corrections resulting from possible differences in the gain of individual preamplifiers. In order to correct the higher orders effects (e.g. differences in the resistance of various electronic components of the circuitry), he uses an iterative calibration method for measuring asymmetry in the "z" direction similar to that used for the "x" and "y" coordinates. Despite of implementation of the advanced calibration and corrections for various contributions to the measurement of the charge asymmetry, the Author could not avoid the significant dependence of the position resolution in the "z" direction on the amplitudes of recorded signal. He realized as well the significant impact of electronic noise and baseline fluctuation on the obtained resolution. The differences in position resolution measured for individual anode wires are also remarkable. Additionally, the efficiencies for determining the "z" component of the particle track (0.75 – 0.85) are decreased in comparison to the value for "x-y" plane (>0.97). Mr. Perkowski correctly concluded that for planned measurement of the beta spectrum the modifications in the construction of readout electronics are demanded. Application of a digitizer of a broader dynamic range is required as well. Worth to consider is even the different method of digitizing of the collected charge value. In this respect the replacement of ADC by a TDC and utilizing the Time-over-Threshold method for extraction of the value of collected charge is foreseen.

The PhD Candidate checked the quality of three-dimensional track reconstruction for the entire detector both for cosmic radiation and for the ^{207}Bi point-like source of electrons. He has obtained slightly better spatial resolutions than those for individual drift cells, which is the expected effect. He also correctly interpreted the small shape distortion of the event distributions recorded at the surface of the scintillator. The image of a point-like source of ^{207}Bi shows the periodic structure which is not present for extended radiation source of cosmic muons. The reason of this distortion are the edge effects in the drift cells where detection efficiency is low and r-t calibration is disturbed. Similar effects were also observed for other multilayer drift detectors with a periodic structure.

Summarizing:

The advantages of doctoral dissertation of Maciej Perkowski are as follows:

- 1) contribution to the fundamental research of weak interactions and the search for effects beyond the Standard Model;
- 2) careful examination and optimization of the prototype of detection system foreseen for difficult and precise measurements;
- 3) identification of the limitation of the detection apparatus including the spectrometer, the tracker, the signal readout circuitry and the data acquisition system. Conceptualization of necessary improvements;

- 4) definition of systematic contributions affecting the accuracy of the results. Their measurement or estimation;
- 5) development of analytical methods for selection and verification of events. Creating of advanced calibrations and corrections algorithms;
- 6) preparation of a control software for components of detection apparatus;
- 7) creation of the user interface that facilitates the data selection, the use of analytical tools and the visualization of results;
- 8) clear and precise reasoning;
- 9) high scientific and instructional merit.

A certain drawback of this PhD thesis, as I have already mentioned, is too concise treatment of the spectroscopic part of the detection system. It would be also interesting and perhaps important to estimate the impact on the final precision measurement the energy losses of beta particles in the selected gas mixture.

Despite of these, in fact, minor shortcomings I affirm that dissertation of Mr Maciej Perkowski satisfies the formal requirements for doctoral theses. The general high scientific value of his dissertation allows me to apply for his admission for the public defense.

