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Review report on Ph.D. thesis of Maciej Perkowski
entitled
**„Precision measurements of the electron energy distribution
in nuclear beta decays”**

Search for effects beyond the Standard Model of elementary particles has become one of the central topics in modern physics. In addition to searches at high energy accelerators, tests of the Standard Model are being done in low energy precision measurements.

An example of such measurements is the determination of the electron energy distribution in nuclear beta decays. Deviation of the spectrum shape from prediction of the Standard Model, corresponding to a non-zero value of the Fierz term, indicates for the impact of exotic interactions not included in this model.

Precise measurement of electron energy distributions in beta decays is a goal of the miniBETA experiment, which is being prepared by the team of prof. Bodek from the Jagiellonian University in collaboration with the Weak Interaction Group led by prof. Severijns from the Catholic University of Leuven. Both groups have been cooperating for many years in the study of the weak interactions at low energies and have brought many important contributions in this field.

The key feature of the miniBETA experiment is the use of a plastic scintillator for measuring the electron energy. The advantage of such scintillator compared with heavier materials is the relatively small energy leakage due to the backscattering of electrons. The energy resolution of plastic scintillators is inferior when compared with e.g. semiconductor detectors but is sufficient to achieve a high precision of the beta spectrum measurement at the level of 10^{-3} to compete with high energy studies performed at the LHC.

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The main subject of Mr. Perkowski's doctoral dissertation was the commissioning of the miniBETA spectrometer. It was not a trivial task, among others due to the use of the ultra-thin drift chamber designed for this spectrometer to minimize energy losses of tracked electrons.

The thesis consists of eight chapters that are preceded by an abstract and ends with an appendix containing a table with detailed analysis results and a list of references.

In Chapter 1, a short overview of the miniBETA project is given and Chapter 2 presents the theoretical background of the project including a brief introduction to the Standard Model, a description of nuclear beta decay based on this model and the impact of hypothetical interactions, not included in the Standard Model, on beta decay spectra.

Chapter 3 is devoted to description of the miniBETA spectrometer consisting of a plastic scintillator and a multi-wire drift chamber. The presentation of the spectrometer design is preceded by an introduction including a brief history of the development of tracking detectors, a description of the interaction of charged particles in matter, and a presentation of basic physical processes in gas detectors. The miniBETA drift chamber consists of 10 detection layers, each containing 8 drift cells with hexagonal shape and a width of 17.3 mm. Sense wires are made of chromium-nickel alloy providing relatively high resistivity, which allows to use the charge-division technique to determine the track position along the wire. To minimize energy losses of particles, the working gas mixture is based on helium with an admixture of isobutane as a quencher. Additional reduction of energy losses is achieved by lowering the working gas pressure to a fraction of atmospheric pressure. The signals from both sense wire ends are amplified and shaped in front-end cards and their amplitudes are measured in the ADC providing the information used in the charge division technique. Besides, the sum of the signals is fed to the discriminator, which generates the stop signal for the TDC to determine the drift time with respect to the start signal derived from the scintillation detector.

In chapter 4, initial tests of the drift chamber performance are presented. These tests were focused on a counting efficiency of the detection plane measured as a function of the high voltage on the sense wire for various helium and isobutane ratios in the applied gas mixture. The measurements were done for a single detection cell illuminated with electrons from a ^{45}Ca source. The normalization of the counting efficiency was based on the counts of the scintillation detector. Signals from the tested drift cell and the scintillation detector were registered using the miniBETA DAQ system and independently, for cross-checking, with the FASTER DAQ module. After subtracting after-pulses and noise pulses from the drift cell counts, the counting efficiency determined for gas mixtures with isobutane content of at least 30% reaches a plateau as a function of the high voltage. The author

suggests, that the after-pulses may originate from the secondary emission of electrons from elements of the chamber, as evidenced by the increase of the number of after-pulses with a decrease of the content of isobutene, which acts as a quencher. The observed delay of the after-pulses with respect to the trigger of 1200 ns and more, as visible in figure 4.5, is not quantitatively explained but this would probably require very complex simulations. The last topic presented in the chapter are corrections of the high voltage supplied to individual detection layers in the full configuration of ten layers in order to compensate for differences in the counting efficiency between layers. These differences result from different capacitance of sense wires in the external and internal planes.

In chapter 5, the drift time-distance calibration of the chamber and the track reconstruction in the plane perpendicular to signal wires based on the drift time measurement are described. The chamber calibration was done by an iterative procedure. The initial calibration was obtained by uniform irradiation of the chamber with cosmic muon tracks and then, in a few iterations, corrections to the initial calibration were calculated based on the mean differences between measured and fitted track distances to sense wires. To improve the precision of the track reconstruction, the measured drift time was corrected for the time walk effect resulting from the relatively long peaking time of the chamber pulses of about 50 ns using the information about the pulse amplitude registered in the DAQ system. The reconstruction of muon tracks was used to determine corrections to positions of individual sense wires and obtained corrections were mostly smaller than 0.1 mm, which is a good proof of the high positioning precision of sense wires. The tracking performance of the chamber was quantified by determining the position resolution and the detection efficiency for the muon tracks and was checked for two different gas pressures of 300 and 600 mbar and, for each pressure value, two different He-isobutane ratios. The best performance was obtained for the two gas mixtures at the gas pressure of 600 mbar. The position resolution is of about 0.4 mm at distances from the sense wire larger than about 4 mm, and it gets worse at shorter distances which can be expected considering the limited statistics of the primary ionization electrons. The detection efficiency is close to 100% and only at larger distances from the sense wire it decreases due to the weak electric field at the cell border.

Chapter 6 presents the reconstruction of particle trajectories in the sense wire direction, using the information about the track position along the wires measured by the charge division technique. Experimental procedures for correcting the measured positions for differences in baseline level and gain of preamplifiers were developed and applied. Besides, the measured positions were corrected for other systematic effects, caused e.g. by additional resistances in the preamplifier input circuit, based on the residuals obtained in the reconstruction of cosmic muon tracks. It was observed that, as expected, the spatial resolution improves for larger registered charges. It was shown,

that the observed differences between channels in the spatial resolution originate from differences in the preamplifier noise level.

To check the track reconstruction in three dimensions, the distribution of track position at the scintillation detector surface was determined. The distribution has a rectangular shape corresponding to the shape of the scintillator. In the measurement of tracks of electrons from ^{207}Bi source, the distribution shows a periodic structure probably originating from lower detection efficiency at the drift cell edges and imperfections of the drift time-distance calibration in the vicinity of the sense wire.

In chapter 7, a procedure of energy calibration of the scintillation detector with electrons from ^{207}Bi isotope is described. It is based on the fit of the measured energy spectrum with the simulated spectrum convoluted with a function describing the energy resolution of the detector. The energy response of the detector shows a very strong dependence on the position of electron interaction in the detector resulting from lack of uniformity in the scintillation light collection. Necessary changes in the detector design to improve the homogeneity of the detector response are described. The estimated precision of the energy spectrum shape measurement is about $5 \cdot 10^{-3}$. To achieve the precision of 10^{-3} required to reach the physics goals of the research program, an upgrade of the detection system is being conducted. The impact of the electron backscattering effect on the performed energy calibration and the estimated uncertainties is not discussed by the author.

In Chapter 8, the last one, the most important conclusions from the performed tests of the miniBETA detection system are collected. The non-homogeneity in the spectrometer response is indicated as the most critical factor limiting the precision of a spectrum shape measurement. In the next version of the miniBETA spectrometer this problem will be greatly reduced by appropriate modification of the light collection from the scintillator.

Turning to the assessment of the dissertation, I would like to emphasize its high level, in particular in its most extensive part regarding the analysis of the drift chamber data. The analysis is conducted in a rigorous and transparent manner. Many clever methods and procedures have been developed for calculating corrections for various systematic effects such as the experimental method for correcting the gain balance for preamplifiers.

The particle tracking in the miniBETA spectrometer was successfully commissioned. Despite the use of the gas mixture with low Z and at reduced pressure, high detection efficiency exceeding 99% was achieved in most of the drift cell. The accuracy of the particle tracking based on the drift time measurement was about 0.4 mm for gas mixtures at 600 mbar and the precision of tracking using the charge division technique was an order of magnitude worse but still reasonable for this technique. The obtained results form a solid basis for the successful realization of the miniBETA project.

The presented research connected with the commissioning of the miniBETA drift chamber, which is characterized by very low material budget, is also an important contribution in the field of particle detectors.

The work is well structured and written using very clear and precise language. I found only one statement, which is not sufficiently justified and, in my opinion, incorrect. Namely, on page 96, after the formula 6.2, the following explanation is given:

"During the avalanche, the same number of positive ions as electrons is created, however, the drift velocity of positive ions is about 1000 times lower than the drift velocity of electrons. Therefore, the influence of the ions on the induced current measured in the setup can be neglected when fast preamplifiers are used."

Due to the high mobility of electrons and the proximity of the avalanche region to the sense wire, the pulse generated by the movement of electrons to the wire is very short, in the order of 1 ns and typically represents a few percent of the total charge induced by the movement of positive ions from the avalanche region to the cathode. Due to the characteristic $1/t$ dependence of the current induced by the positive ions, even if this current is integrated over the first 100 ns as in the current system (see page 34, line 14) the total charge may be a few times higher than the one induced by electrons.

A description of the performed studies is at appropriate level of details.

Only Chapter 4 on the initial tests of the chamber performance could contain more details for more interested readers.

In my opinion, the author could present a figure with examples of pulses from the tested drift chamber so that the reader could get a better feeling about the shape of pulses, their duration, the level of noise and possible distortions. Also, the information about the number of ionization electrons for minimum ionizing particle crossing the cell would be useful for an easy comparison with standard gas mixtures based on argon at atmospheric pressure, with the number of ionization electrons of roughly 100 per 1 cm track length.

However, I would like to point out that the above suggestions for the additional information are largely subjective and presumably stem from my interest in drift chambers.

The text is very carefully edited. I found only two typos:

- on page 76, line 14 the reference to Fig. 5.15 is incorrect. It should probably be Fig. 5.3.
- on page 91 in the text and in the table 5.3, after the expression " $\xi > 3 \text{ mm}$ " symbol of squaring is missing (it should be $\xi > 3 \text{ mm}^2$).

These shortcomings and typos do not significantly affect the value of the thesis.

In conclusion, the dissertation presented by Maciej Perkowski contains valuable and original results and satisfies the formal requirements for doctoral thesis and hereby I recommend admitting it for the public defense.

A handwritten signature in blue ink, appearing to read 'Jerzy Smyrski', is positioned above the printed name.

/Jerzy Smyrski/