Search for beyond standard model physics in free neutron decay

A. Kozela[1], K. Bodek[2], J. Choi[5], L. DeKeukeleere[3], K. Dhanmeher[1], M. Engler [6], G. Gupta[2], K. Łojek[2], K. Pysz[1], D. Ries[6], D. Rozpędzik [2], N. Severijns[3], T. Soldner[4], B. Włoch[1], N. Yazdandoost[6], A. R. Young[5] and J. Zejma[2]

[1] H. Niewodniczański Institute of Nuclear Physics, Kraków, Poland
[2] M. Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland
[3] Institute of Nuclear and Radiation Physics, KU, Leuven, Belgium
[4] Institut Laue-Langevin (ILL), Grenoble, France
[5] Dep. of Physics and Astronomy, North Carolina State University, Raleigh, USA
[6] Dep. of Chemistry, TRIGA site, J. Gtenberg University, Mainz, Germany

E-mail: adam.kozela@ifj.edu.pl

Abstract. Applying a Mott polarimetry for measurement of the transverse polarization components of electrons from free neutron decay as well as proton momentum reconstruction using the combination of the time of flight method and the kinematical constrains of this three body decay, one gets access to eleven correlation coefficients of the neutron β-decay. Successful measurement of some of these coefficients would allow for an unique access to exotic scalar and tensor couplings of weak interactions and obtaining new constraints on their imaginary part, known with much worse accuracy. Results of the performance studies of some key experimental components of the prototype setup performed during the test run in 2021 at ILL PF1B neutron beam line are presented.

1. Introduction

Rich experimental evidence indicates that the Standard Model description of combined CP symmetry and, assuming CPT theorem, also time-reversal symmetry (T) is incomplete. Search for new sources of CP and T symmetry violation constitutes the main motivation of many experiments already performed, ongoing or planned. Sizable contribution of heavy quarks, inevitably created in high energy experiments, interfere in the dynamics of the observed processes and makes the distinction between the new physics and the SM induced effects difficult in this energy domain. As the heavy quark content in nuclear matter is almost negligible, the nuclear β-decay experiments are practically free from this hindrance, enhancing interest in β-decay as the tool for new physics searches. The decay of the free neutron plays a particular role in this field: due to its simplicity it is free from model-dependent corrections associated with the nuclear and atomic structure. Moreover, the final-state interaction induced effects, which can mimic T violation, are small in this case and can be calculated with relative precision better than 1% [1]. There is no doubt that the discovery of new CP- or T-violating phenomena in such a system would be an important milestone. The observables of interest in this case are angular correlations in neutron decay, especially those involving three vectors, as they can be linked to exotic couplings which are a potential source of the time reversal violation.

A new approach to search for scalar and tensor couplings of weak interaction is being prepared at ILL Grenoble by the international BRAND collaboration [2]. This experiment proposes an unprecedented attempt to kinematically complete reconstruction of neutron decay events by measuring electron and proton momenta and, additionally, electrons' transverse polarization components. This extends the idea of the former nTRV experiment [3] which focuses on the T- and P-odd R-correlation coefficient, by means of Mott polarimetry [4], dedicated to electrons from free neutrons decay. Reconstruction of coincident proton momentum increases the number of correlation coefficients accessible in BRAND to eleven, from which five have never been attempted experimentally. The large number of measured coefficients not only enhances the credibility of this experiment, but also facilitates the interpretation of the result obtained, as different coefficients depend on exotic couplings in a different way.

This paper presents the results of a feasibility study of the key components of the prototype BRAND detectors. The experiment has been performed in 2021 at ILL, Grenoble, on the PF1B cold neutron beam line. This paper focuses on the part of the setup devoted for β-particles, namely on the Mott polarimeter.

2. Principle of BRAND experiment

Final realization of the BRAND experiment requires application of detectors able to reconstruct momenta of extremely low energy protons and electron momenta of two kinds of events: direct electrons from neutron decay and electrons scattered in Mott process from a thin layer of heavy element e.g. lead. In order to detect the β-decay protons of energy below 800 eV a dedicated configuration of electric field will be prepared with the aim to provide a free flight path and, subsequently, their acceleration by 25 kV high electric potential. Accelerated protons are directed towards a hundred nanometer thick converter foil [5], from which they knock out of order 10 secondary electrons. These electrons are subsequently accelerated by the same high potential towards a grounded, position sensitive scintillator detector. Good timing information is mandatory for this detector, as from the known time-of-flight and protons trajectory its initial momentum will finally be reconstructed.

This concept assumes also the knowledge of the neutron decay vertex, which can approximately be reconstructed from the intersection between the reconstructed electron trajectory and the fiducial neutron beam volume. Applying additional constraints imposed by 3-body decay kinematics will allow further increasing accuracy of the reconstructed vertex position.

3. Test setup

The experimental setup consisted of a large cylindrical vacuum chamber with three ports on its side wall equipped with proton detector prototypes, an electric potential cage and a large area vacuum exit window for electrons from neutron decay (Fig. 1). Dedicated current-carrying coils around the chamber and the beam line provide the axial, spin holding magnetic field necessary to maintain longitudinal polarization of the cold neutron beam centered around the axis of the chamber.

Directly in front of the electron exit window the Mott polarimeter was installed. It consisted of an electron tracker, the Back Scintillator (BS), two Mott Scintillators (MSs) installed symmetrically face-to-face, and the Mott target situated between the sixth and seventh plane of the tracker.

The tracker is a low density drift chamber with eight measuring planes, with the configuration based on the miniBETA spectrometer [6]. Each measuring plane consisted of twelve drift cells of hexagonal structure with 25 μm chromium-nickel anode wires and 75 μm copper-beryllium

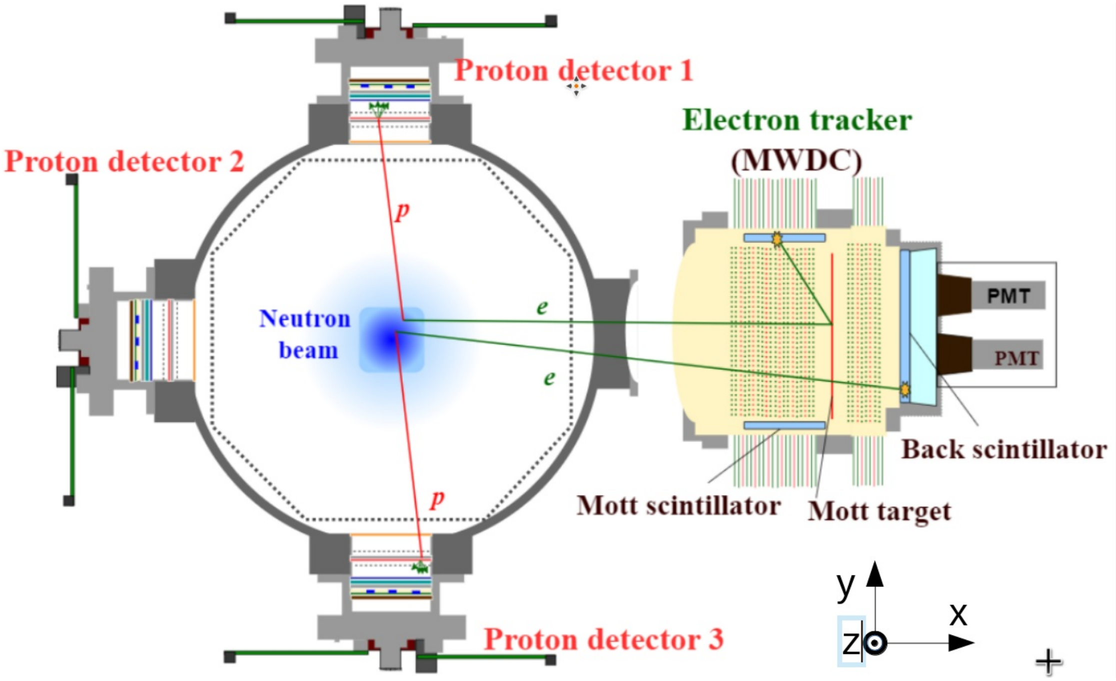

Figure 1. Cross section view (along the beam line) of the test setup used in 2021 at PF1B areal. Sample events with direct electron stopped in Back Scintillator and electron scattered from Mott foil and registered in Mott Scintillators are shown.

cathode wires. The maximal effective drift radius of each cell was equal to 8.66 mm. The hexagonal cell structure and the helium-based gas mixture were optimized for registration of low energy electrons. The track position determination in the xy-plane was realized by conventional drift time measurement, whereas the both-end readout of anode wires allowed for application of the charge division method for position reconstruction in z-coordinate along the wire.

Both the BS and the MSs are intended to measure the energy of electrons and provide the trigger signals for the data acquisition system. They are made of 10 mm thick plastic scintillating material. BS is of circular shape and has diameter of 200 mm. MSs are rectangles of 200 x 100 mm side lengths. The light created in BS is collected by four conventional 3-$inch$ PMTs. In case of MSs the light sensors are the arrays of 14 SiPMs attached to the shorter side-walls of the detectors.

The Mott target is made as a 2 μm thick Pb-film deposited on the 4 μm thick Mylar substrate. The foil is stretched on a rectangular frame and attached to a mechanism permitting its moving-in/out without disturbing the working conditions of the tracker.

Custom made front-end electronics reads both the amplitude and time information of the analyzed signals. The signal amplitudes were converted to time and digitized by 128-channel 1129 CAEN TDC units.

4. Detector performance

4.1. Position resolution

In order to improve accuracy of track reconstruction from the drift time information, a standard iterative procedure minimizing reconstruction residua has been applied for each drift cell separately. A sample of achieved typical position resolution from the drift time (in y-coordinate) along the cell radius is shown in Fig. 2a. The hit position along the wire length (z-coordinate) was calculated from the collected charge asymmetry at both ends of the wire. Also in this case the position calibration has been performed for each wire separately based on dedicated calibration runs with electrons from ^{207}Bi source. An example of obtained dependence of position resolution on the hit position along the wire is presented in Fig. 2b.

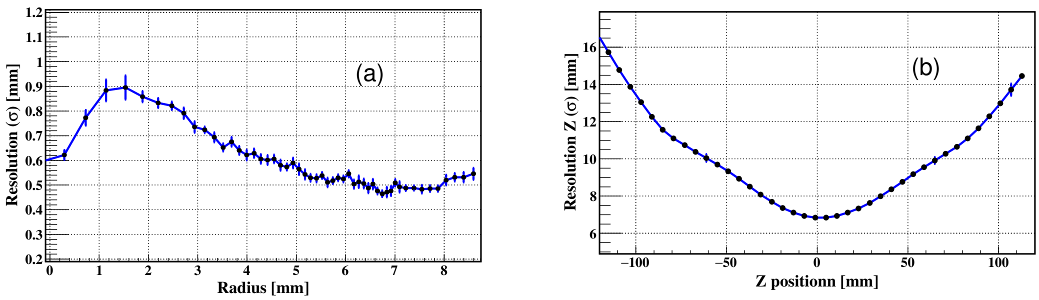

Figure 2. Typical dependence of obtained position resolution from drift time information (for y-coordinate) as a function of the drift distance (a). Typical dependence of obtained position resolution from charge division method (for z-coordinate) as a function of the hit position along the wire length (b).

The typical cell detection efficiency is higher than 90%. The tracking efficiency of the tracker is biased with the quality of recorded signals. For reasonable tracking criterion the tracking efficiency is of the order of 70%.

Although a reasonable starting point for development, significant improvements in the noise level, signal readout and processing, and charge measurement are required for BRAND (with improvements already underway).

4.2. Energy spectra

Due to significant position dependence of light collection in PMTs of the BS the partial energy spectra for a selected small area of BS surface had to be considered. All shown in the following examples of energy spectra were obtained for the central region of BS with diameter of 10 mm, as reconstructed by the electron tracker.

The energy calibration and estimation of energy resolution could be obtained from measurements of energy spectra with a ^{207}Bi source, emitting conversion electrons of discreet energies. Two of the energy lines of ^{207}Bi are dominant and should be resolved with the plastic scintillation detector.

Fig. 3a shows the measured ^{207}Bi spectrum superimposed on the measured spectrum of electrons induced by neutron beam. For comparison, the relevant results of Geant4 simulations with realistic geometry and energy smearing, reproducing the 1 MeV electron line of ^{207}Bi, are shown as well. This spectrum allows for energy calibration of electron spectra recorded in the selected area of the BS. From the position and the width of the 1 MeV electron line of ^{207}Bi the energy resolution is calculated to be of the order of 16%.

In Fig. 3b the measured β-spectrum from the neutron beam is shown after background subtraction.

The background identification is crucial in the BRAND experiment. The γ radiation can be suppressed via passive shielding, selection of trigger conditions and proper energy cuts. Particularly difficult is the background created due to β-decay of unstable isotopes. They are produced in neutron capture in the interior of the vacuum chamber and in the surrounding experimental infrastructure. The most effective tool for rejection of this kind of events ultimately will be the requirement of electron-proton coincidence. Since currently the proton detection part of the BRAND setup is still in the R&D phase, this method could not be utilized.

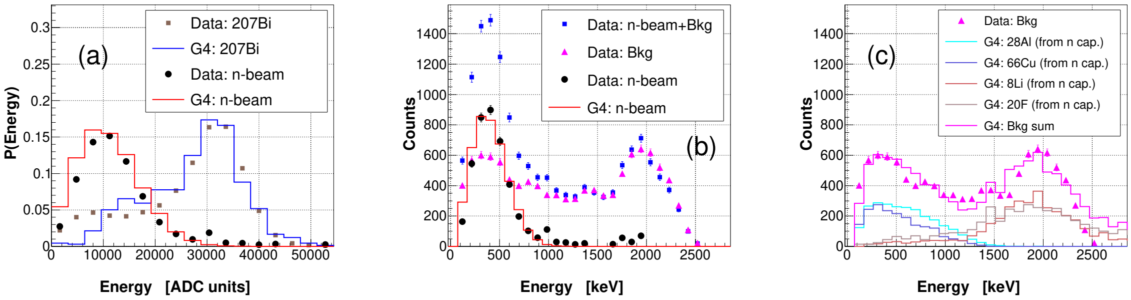

Figure 3. (a): β-spectrum of free neutrons (black dots) and ^{207}Bi electron conversion spectrum (brown squares) measured in the middle area of BS. The corresponding distributions from Geant4 [7] simulations are superimposed (solid lines). Actual energy spectrum contaminated with the background, measured in the middle of BS (blue squares) compared to the background spectrum measured in the same area (magenta triangles) (b). The β-spectrum of neutrons (black dots) is a result of subtraction of the latter from former distributions. Background distribution recorded in the middle area of the Back Scintillator (triangles, magenta) compared to results of Geant4 simulations (c). Included are components from β-decay of ^{28}Al, ^{66}Cu, ^{8}Li and ^{20}F.

Estimation of the background component of energy spectra is performed currently by the position cuts selecting electrons from inside and outside of the fiducial beam volume, and subsequent comparison of the obtained energy distributions. Finally the quality of background identification has to be confirmed by comparison of the resulting β-spectrum of neutrons with the Geant4 simulation. This is shown again in Fig. 3b (red line).

Observation of background intensity decay after switching off the beam has shown that the dominant components in the lower energy range come from ^{27}Al+n$\rightarrow^{28}$Al$\rightarrow^{28}$Si, β, γ and ^{65}Cu+n$\rightarrow^{66}$Cu$\rightarrow^{66}$Zn, β, γ reactions. This is supported by Geant4 simulation as shown in Fig. 3c. Aluminum is a dominant construction material used for the decay chamber and HV cage. The copper can be found in aluminum alloy building the chamber wall and in the HV cage (printed boards, wires). For energies higher than the neutron β-spectrum a significant background was visible. In performed Geant4 simulations this component was tentatively identified as electrons from ^{7}Li+n$\rightarrow^{8}$Li$\rightarrow$ $2\alpha\beta, \gamma$ and ^{19}F+n$\rightarrow^{20}$F$\rightarrow^{20}$Neβ, γ reactions, elements present in the beam dump. The ultimate identification of the origin of high energy electrons in the interior of BRAND decay chamber is not completed and corresponding analysis is ongoing. The bump around 2 MeV is an effect of limited width of the BS scintillator insufficient to stop higher energy electrons. It should, however, be stressed that low resolution and limited energy range of the scintillator do not preclude other sources of high energy electrons.

The energy spectra and the background distributions recorded in the MSs are of lower quality than those of BS. The estimated energy resolution is by a factor of about two lower then for BS detector. This is predominantly due to its worse light collection efficiency.

Obtained low energy resolution of both the BS and MSs lead us to the conclusion that their front-end electronics used for signal readout and processing needs further optimization. Since similar readout scheme is applied also in front-end electronics used for the charge division method, this can also contribute to the explanation of the lower than anticipated electron tracker position resolution along the z-axis.

4.3. Mott polarimetry

In order to determine the transverse component of electron spin the left-right asymmetry in the Mott-backscattered electrons from a heavy element of spin zero (Pb in case of BRAND) must be measured. This asymmetry, A_m, is proportional to an effective Sherman function, $S_{eff}(\theta)$. The Mott scattering cross section, $\sigma(\theta)$ depends on the scattering angle θ.

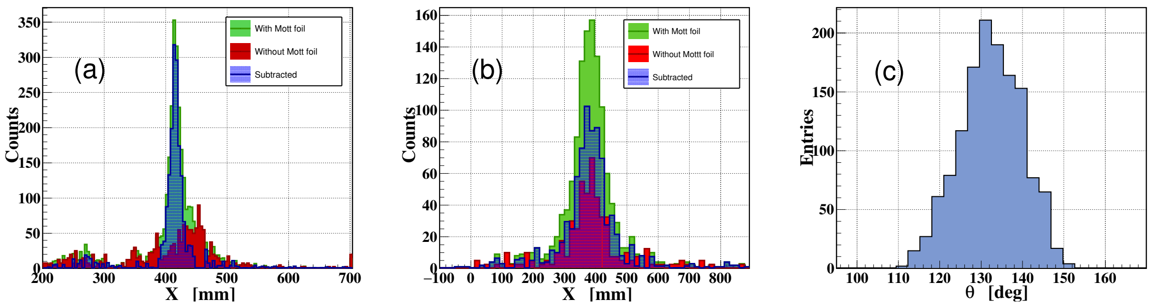

Figure 4. Reconstructed distribution of the Mott scattering vertices for runs with and without Mott foil: in y direction (a) and in z direction (b). Sum of angular distributions of electrons back-scattered at the Mott target and registered in both MSs (c).

The distributions shown in Fig. 4 present the current potential of Mott polarimetry in BRAND experiment. The reconstruction of the scattering vertex in y direction follows the decent position resolution based on drift time measurement and allows for the determination of Mott scattered electrons with sufficient confidence (cf. Fig. 4a). Vertex reconstruction in z-coordinate is biased with significantly lower position resolution from the charge division method. Also a systematic displacement of the reconstructed vertex position is observed - see Fig. 4b. Fig. 4c shows the Mott-scattering angle distributions of electrons accumulated in both MSs. The obtained angular range ($\sim 110°$ - $150°$) assures large Mott cross section $30 < \frac{d\sigma}{d\Omega} < 2000$ b sr^{-1} with still appreciated analyzing power -0.5 $< S_{eff}(\theta) <$ -0.2 and in consequence efficient polarimetry of electrons from free neutron decay.

5. Conclusions

The preliminary results of the test experiment of the prototype BRAND apparatus performed in ILL Grenoble in autumn 2021 confirmed in general the feasibility of proposed experimental method aimed at the search for exotic components of week force foreseen in BSM physics.

Identified are areas where improvement is needed. Special attention has to be paid to the charge division method applied for z-coordinate reconstruction and to the readout electronics where current method of signal processing aimed at signal amplitude-to-time conversion needs a revision. The development of challenging proton detection system - crucial for the success of the experiment - is ongoing.

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