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Mott-polarimeter for electrons from neutron decay in BRAND experiment

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The BRAND experiment aims at the search of Beyond Standard Model (BSM) physics via measurement of exotic components of weak interaction. For this purpose the eleven correlation coefficients of the neutron β decay will be measured simultaneously. Seven of them: *H, L, N, R, S, U* and *V*, are sensitive to the transverse polarization of electrons from free neutron decay. The correlation coefficients will be derived using Mott polarimetry and completely determined kinematics of products from the polarized neutron β decay. For this aim the beam of cold polarized neutrons available at the PF1B facility of the ILL, Grenoble will be utilized.

The electron detection system features both the tracking and energy measurement capability as well as the Mott polarimetry for determination of the electron spin orientation. The 3D tracking is performed with the use of low density, helium based drift chamber with hexagonal cell structure which is optimised for β-particles. The Mott polarimeter is an integral part of the tracker. It consists of a thin Pb foil installed inside the drift chamber and two plastic scitillators, providing trigger and scattered electron energy measurement.

The results of the first pilot run of the BRAND experiment performed in September'20 are reported with the emphasis on the description and the performance of the electron detection system and the Mott polarimeter.

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1. Introduction

Within the frame of contemporary minimal version Standard Model (SM) of fundamental interactions, some significant problems remain unsolved. Among them are the reason of observed matter/antimatter asymmetry in the Universe, unknown mechanisms responsible for CP violation, the origin and hierarchy of lepton masses, number of fundamental hadron/lepton generations.

The BRAND experiment shall contribute to the possible extension or modification of SM by providing precisely measured observables in the sector of electroweak interactions. The strength of the conventional and exotic components of weak interaction is probed by measurement of the correlations of momenta and spins in the decay of free polarized neutron. With fully kinematically reconstructed β decay of neutron, including four-momenta of electron and proton, and components of transverse polarization of electrons, the BRAND experiment is sensitive to those component of weak interactions, which are not foreseen in the current *V-A* (vector minus axial vector interactions) formulation of SM. If the measurement of interaction components having the scalar (*S*) or tensor (*T*) symmetry properties occur to be finite, this will show the limitations of SM, demanding its extension and indicating physics beyond the Standard Model (BSM).

According to [1] when the detection system is sensitive for the above-mentioned kinematical parameters of β decay, the differential decay rate of oriented neutrons can be expressed as:

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\upsilon} \sim 1 + a\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\upsilon} + b\frac{m_e}{E_e} + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}}{E_e} + B\frac{\mathbf{q}}{E_\upsilon} + D\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\upsilon}\right]$$
$$+\sigma_\perp\left[H\frac{\mathbf{q}}{E_\upsilon} + L\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\upsilon} + N\frac{\langle\mathbf{J}\rangle}{J} + R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}}{E_e} + S\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\upsilon} + U\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\upsilon} + V\frac{\mathbf{q}}{E_\upsilon}\times\frac{\langle\mathbf{J}\rangle}{J}\right], \tag{1}$$

where $\frac{\langle\mathbf{J}\rangle}{J}$ is the polarization of neutron beam, $\sigma_\perp$ represents the transverse component of electron spin (orthogonal to its momentum vector), E_e and $\mathbf{p}$ are energy and momentum of electron, respectively, and the E_υ and $\mathbf{q}$ are (kinematically reconstructed) energy and momentum of anti-neutrino.

In this way 12 correlation coefficients, namely $a, b, A, B, D, H, L, N, R, S, U, V$ can be measured. Except a, all of them in the first order approximation can be expressed as:

$$X = X_{\text{SM}} + X_{\text{EM}} + c_{ReS}\text{Re}S + c_{ReT}\text{Re}T + c_{ImS}\text{Im}S + c_{ImT}\text{Im}T, \tag{2}$$

where, beside of the conventional SM components and the contribution due to electromagnetic interactions in the final state, the linear combination of the real and imaginary components of exotic scalar (*S*) and tensor (*T*) couplings contribute.

The BRAND experiment in its ultimate status will simultaneously measure 11 coefficients. For those - sensitive to transverse electron polarization the accuracy will be of 5×10^{-4}. It will provide the experimental limits on the strength of possible time reversal symmetry violating processes. The results of BRAND experiment will also be utilized for constraining of the leptoquark exchange models and to tune the parameters of effective field theories (EFT) which provide the common formalism both for high and low energy fundamental research.

The proposed setup of ultimate BRAND experiment [2] will consist of elements which are optimized for the measurement of the transverse component of electron polarization and the four momenta of the decay products (protons and electrons). The key features of the setup (see Figure 1) will be: (*i*) azimuthal detection acceptance of 360° around highly polarised cold neutron beam; (*ii*) helium based low density multiwire drift chamber (MWDC) for 3D tracking of emitted electrons;

(*iii*) embedded Mott polarimeter with thin target of high atomic number Z; (*iv*) energy spectrometers (scintillators); (*v*) proton detector utilizing the conversion of accelerated protons into bunches of δ-electrons ejected from the LiF layer of an ultra-thin conversion foil.

2. Prototype apparatus - BRAND-0

In September 2020, short test measurement (5 days) with the use of a prototype of BRAND apparatus was performed at neutron facility (PF1B) of Institut Laue-Langevin (ILL), Grenoble. A polarised cold neutron beam with flux 6.3×10^8 n/cm^2/s and cross-section 6×6 cm^2 was used for this purpose. Figure 2 shows the BRAND-0 setup. The principle of BRAND experiment was tested with a prototype of the Mott polarimeter and a prototype of the proton detector. In this paper the performance of the electron Mott polarimeter is presented, whereas the construction and performance of the proton detector is described in the contribution of D. Rozpędzik to this conference.

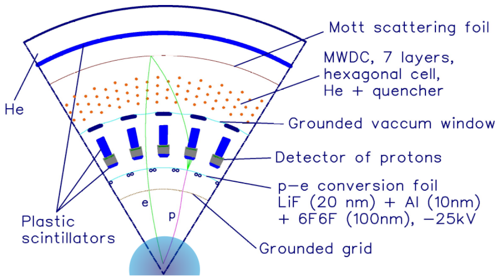

Figure 1: The arrangement of planned detection system of BRAND experiment. Only one sector ($1/6^{th}$) of the fully axially symmetrical setup is presented.

The cold neutron beam was aligned along the axis of the cylindrical BRAND vacuum chamber. A fraction of electrons from the neutron decay could leave the decay chamber through the thin side windows (10 μm thick aluminized Mylar) and were registered in the electron detector (see Figure 2). The detector featured both tracker and spectrometer capabilities serving at the same time as the electron spin analyzer. Electron's transverse spin component was measured by the Mott polarimetry.

The orientation of electron tracks was measured in low density helium based (He:CO2 (85:15) + trace of ethanol vapours) gaseous detector operated at ambient pressure. It was built as an 8 layer drift chamber of hexagonal cells. Anodes positioned in the center of hexagon collected the electron current induced by initial ionization of the gas medium in the electric field formed by grounded cathode wires located in the corners of hexagon. The track position in XY-plane was extracted from the measured drift time of primary electrons whereas the position along the wire length (YZ-plane) was obtained by means of the charge division technique. The tracker prototype was a copy of the miniBETA spectrometer [3, 4]. Its properties are optimized for the energy range of electrons emitted in β-decay.

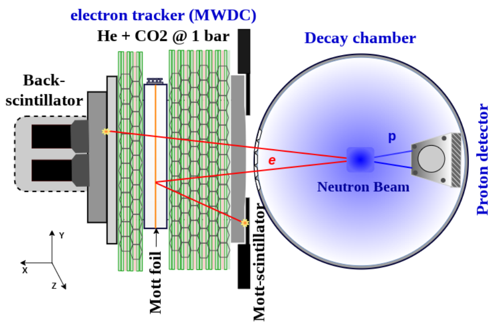

Figure 2: Prototype of the detection system used during the first pilot run at ILL Grenoble in September 2020.

The Mott target (2 μm of Pb evaporated on 4 μm thick Mylar foil) was installed inside the tracker between its 6^{th} and 7^{th} layer. Only about 10^{-3} of electrons passing the tracker have been back-scattered by means of Mott scattering. Their back-tracks were registered by the tracker creating so-called *V-tracks*. The energy of scattered electrons was measured in two, rectangular 10 mm thick, symmetrically positioned at front of the tracker, plastic scintillators. The electrons which penetrated the Mott foil without significant deflection were registered in the circular plastic scintillator of 10 mm thickness installed behind the tracker. Both scintillator detectors provided not only the energy of registered electrons but also a trigger for DAQ and the start signal for the drift time measurement.

3. Analysis and Results

The values of the transverse electrons spin component are extracted from angular distributions of Mott-scattered electrons. Thus, the accurate identification of the electrons, which actually have been scattered by Mott interaction is crucial. It is possible by precise tracking, reconstruction of scattering vertices and measurement of the scattering angle (δ) distributions. The effective spatial resolution of MWDC achieved by the drift time measurement is about 0.4 mm . The applied charge division technique provides a position resolution in Z direction of 5.0 mm.

An example of a distribution of *V-track* vertices in the XY-plane is shown in Figure 3. The pronounced peak seen in this distribution is positioned at X = 372 mm, where the Mott foil was installed. The obtained resolution of the vertex reconstruction in X direction is 15 mm. Figure 4 presents the scattering angle distribution for the Mott-scattered electrons.

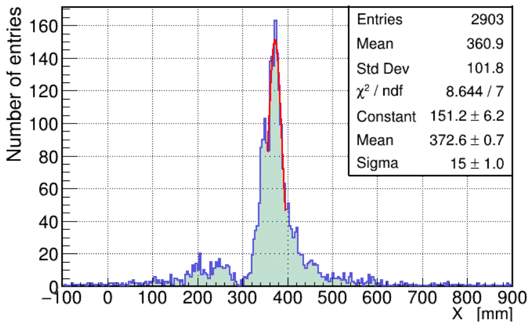

Figure 3: Vertex distribution of *V-tracks* for Mott scattered electrons.

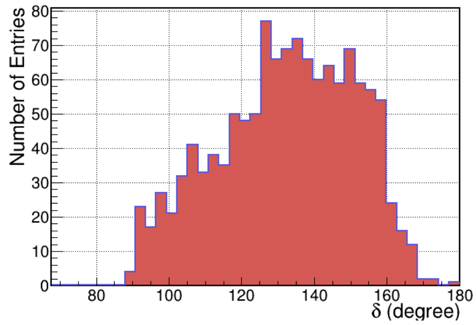

Figure 4: Angular distribution of scattering angles for identified Mott-scattered β-particles.

4. Conclusions and future prospects

Results from the first test run are promising. They prove that the experimental techniques applied for the Mott polarimetry in the BRAND experiment are efficient and precise. After the important upgrades of the above described BRAND-0 setup, the commissioning of the experiment was conducted in autumn 2021. The analysis of the collected data is ongoing.

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