Status Update on the $\beta$-$\nu$ Correlation Measurement in the $\beta$ Decay of $^8$B

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The $\beta$ decay of $^8$B to $\alpha$-unstable $^8$Be presents a unique opportunity to determine angular correlations with unprecedented precision. In this decay, the experimental sensitivity to small deviations from the Standard Model prediction are enhanced by the large $Q$ value of the decay, the small mass of the nuclei involved, and the presence of an additional correlation that arises between the emitted $\beta$ particle, neutrino, and $\alpha$ particles. We present here the current status of the effort to precisely determine $\beta$-$\nu$ angular correlation coefficient ($a_{\beta\nu}$) with trapped $^8$B ions using the Beta-decay Paul Trap at Argonne National Laboratory.

**KEYWORDS:** Beta-decay, fundamental symmetries, angular correlations, trapped ions, precision measurements

Measurements of the $\beta$-$\nu$ angular correlation coefficient ($a_{\beta\nu}$) in $\beta$ decay probe the existence of scalar and tensor interactions that lie outside the vector minus axial-vector ($V - A$) description of the electro-weak sector of the Standard Model (SM). Experiments performed at low energy have placed limits on the coupling constants of these SM forbidden interactions, $C_S$ and $C_T$, at the 5% to 10% level (95.5 % C.L.) relative to the dominant vector and axial-vector components [1]. A positive observation of a scalar or tensor component would be a significant deviation from the SM and might also imply the existence of additional particles [2]. Furthermore, stringent tests of other fundamental symmetries such as the conserved vector current hypothesis and limits on second class currents can be improved by precise measurements of the $\beta$ decay recoil-order terms extracted from comparison of angular correlation coefficients from mirror decays [3].

Measurements of $a_{\beta\nu}$ using trapped samples of neutral and charged radioactive atoms open the possibility of reaching higher levels of precision and sensitivity than previously achieved [4]. Electromagnetic fields confine the particles to a small region of almost empty space, an arrangement that
permits the correlation to be inferred through the determination of the nuclear recoil. Experiments that exploit the advantages of atom and ion traps have determined $\Delta Q_{\beta}$ to precisions of approximately 1% [5–9]. Next-generation experiments are currently underway to reduce the uncertainty by another order of magnitude within a decade [10].

Measurements of angular correlations with a trapped sample of $^8\text{B}$ are particularly compelling for improved searches for deviations from SM predictions. The $J^\pi = 2^+$ first excited state in $^8\text{Be}$ that immediately breaks up into two $\alpha$ particles: $^8\text{B} \rightarrow e^+ + \nu + 2\alpha + 17 \text{ MeV}$. The decay is predominantly Gamow-Teller [11] and hence is sensitive to only a SM-forbidden tensor contribution to the dominant axial-vector current. From coincident detection of the $\beta$ particle and the two $\beta$-delayed $\alpha$ particles it is possible to reconstruct with great sensitivity the nuclear recoil as well as the kinematics event by event and determine the angular correlation between the leptons. The high sensitivity comes from the large $Q$ value of the decay, the small masses of the nuclei involved, and the presence of an additional correlation between the $\alpha$ particles and the leptons that can provide an enhanced contrast between an axial-vector and tensor mediated decay. This additional correlation was first pointed out by Morita [12] and arises because the leptons are longitudinally polarized and therefore leave the spin of the daughter nucleus oriented.

The $^8\text{B}$ decay has also several experimental advantages. The lifetime of $^8\text{B}$ ($t_{1/2} = 770(3) \text{ ms}$ [13]) is long enough that creation, transportation, and preparation of a well-localized trapped sample can be achieved without major losses. The $\beta$-delayed $\alpha$ particles are in the easily measurable 1.5-MeV range. In the laboratory frame, due to the nuclear recoil imparted by the leptons, the energy difference between the $\alpha$ particles can be as large as 400 keV and their relative angle can deviate from perfect back-to-back emission by up to 7 degrees. The symmetry in the decay allows for significant suppression of systematic effects by comparing the measured $\alpha$ particle energy difference with different pairs of detectors. The kinematic shift in $^8\text{B}$ is much larger than those in other experiments that have measured the energy of the nuclear recoil directly [5, 7, 9, 14] or have determined the nuclear recoil from delayed-particle emission [15, 16].

The $^8\text{B}$ experiment takes place at the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory. A 40-MeV $^6\text{Li}$ beam impinges on a cryogenic $^3\text{He}$ gas target to produce $^8\text{B}$ through the $^3\text{He}(^6\text{Li}, ^8\text{B})n$ reaction. The $^3\text{He}$ is held at a temperature of approximately 90 K and at a pressure of 550 Torr. A large superconducting solenoid focuses the $^8\text{B}$ nuclei into a gas catcher where the particles come to rest within a bath of ultra-high purity $^4\text{He}$ gas while remaining charged so that they can be rapidly extracted [17]. A movable beam-stop at zero degrees after the target removes the bulk of the primary beam to reduce the amount of $^6\text{Li}$ that reaches the gas catcher. After the gas catcher, an ion transport system cools, bunches, and transports the ions of interest into the Beta-decay Paul Trap (BPT) [18] where the ions are stored and the actual measurements take place.

The BPT is a linear Paul trap consisting of four sets of segmented planar electrodes (Fig. 1). Along the radial direction, the ions are confined by $dc$ potentials applied on the three segments of each electrode. In the radial direction, the ions are confined by radio frequency ($rf$) fields applied to the electrodes. The BPT is filled with high-purity $^4\text{He}$ buffer gas at a pressure of about 10 $\mu$Torr to reduce the energy spread and volume of trapped $^8\text{B}$. The frame of the trap is cooled to liquid nitrogen temperature which improves the vacuum and reduces the temperature of the He gas. This results in longer storage times and a spatially smaller ion cloud. The ion cloud has a typical spatial spread of approximately 1 mm$^2$. The ion cloud is viewed by four $64 \times 64 \times 1$-mm$^3$ double-sided silicon strip detectors (DSSSDs). The DSSSDs have 32 strips in each face, each 2-mm wide, to identify where the particles strike the surface and therefore allow the reconstruction of the momentum direction of the decay products of $^8\text{B}$. The energy and angular resolution of the system is less than 25 keV FWHM and 1.5 degrees, respectively. The $\alpha$ particles coming from the break-up of $^8\text{Be}$ are completely stopped in the detectors while the $\beta$ particles are not stopped but leave behind some energy that is used for identification. The information provided by the DSSSDs is sufficient to completely determine the
kinematics of the decay.

Prior to the $^8$B campaign we installed a new gas catcher that has been designed to reduce space-charge saturation. The activity observed after the gas catcher with a silicon detector scaled almost linearly with the beam current up to 150 pnA which suggests little or no saturation at these beam currents. Additionally we have a multi-wire proportional chamber (MWPC) mounted in the beam line that can provide information on the yield of products that make it to the gas catcher. The MWPC is very useful in determining the best combination of focusing magnetic field and beam-stop position for the production of $^8$B. The $^8$B yield measured with the MWPC (approximately 2000 $^8$B nuclei per pnA per second) gave results consistent with the yield calculated from the reaction cross section [19]. Furthermore, simulations of the transport of the products of the reactions and the scattered main beam were done using SimIon [20] to help interpret the data from the MWPC and to establish initial experimental parameters. Finally, we have modified the gas target to allow reaction products created at the largest angles to come out unhindered from the gas volume. For a 40-MeV $^6$Li beam, the $^8$B nuclei are emitted within a cone with an opening angle of 24 degrees.

![Cross-section of the Beta-decay Paul Trap and detector array.](image)

Fig. 1. Cross-section of the Beta-decay Paul Trap and detector array.

The detectors are semi-enclosed by two layers of shielding that greatly reduce the rf pickup. Openings on both shields allow the unhindered passage of the decay products to the DSSSDs. Any residual rf pickup is further suppressed by RC filters in the shaping amplifiers that amplify the signal from the DSSSDs before being sent to peak-sensing analog-to-digital converter modules. Two sets of $^\alpha$ sources ($^{148}$Gd and $^{244}$Cm which emit $^\alpha$ particles with energies of 3182.690(24) keV and 5804.77(5) keV, respectively [13]) are mounted on the inner surface of each rf shield to provide continuous in situ calibration of the DSSSDs throughout the data-acquisition process. A precision pulser is used periodically to check the linearity of the electronics.

Figure 2 shows an experimental spectrum of the energy difference between the two $^\alpha$ particles for events where a $^\beta$ particle is detected in the same direction as the $^\alpha$ particles for all detector combinations. The data was taken during a low statistics run performed in early 2013. An event generator code adapted from Ref. [5] is used to generate the expected response for a pure axial-vector or tensor interaction. The event generator code is based on Ref. [21] including the recoil order terms and the order-$^\alpha$ Z-dependent and Z-independent radiative corrections [22]. The simulation also propagates the particles in the geometry of the experiment and determines if they strike the detector. The results show good agreement with the existence of a pure axial-vector current.
In conclusion, we have presented an update on the measurement of $a_{0\nu}$ with $^8$B. This measurement forms part of our program to test fundamental symmetries of the SM using the $A = 8$ isotriplet. We have already performed a proof-of-principle experiment with $^8$Li [6] with an uncertainty within a factor of three of the most precise $a_{0\nu}$ measurement (0.3308(30) at 1-$\sigma$ [14, 23]). We have since acquired around 10 times more statistics with $^8$Li and $^8$B [24]. The $^8$Li data is fully analyzed and a publication is in preparation [25] while the analysis of $^8$B is currently ongoing. High precision measurements of $a_{0\nu}$ in $^8$B and $^8$Li will allow us to perform stringent tests of fundamental symmetries of the SM such as the conserved-vector current hypothesis and to search for second-class currents [1, 3].

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References

[10] See for example N. Severijns contribution in this proceedings.
[24] A high statistics run with $^8$B was performed shortly after the conference.