Discrimination in Liquid Scintillator and Its Usage to Suppress $^{8}\text{He}/^{9}\text{Li}$ Backgrounds

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Abstract: Reactor neutrino experiments build large-scale detector systems to trap ghost-like neutrinos. In liquid scintillator, a neutral bound state of a positron and an electron named positronium could be formed. The spin triplet state was called ortho-positronium (o-Ps). In this script, an experiment was designed to measure the lifetime of o-Ps, which turned out to be 3.1 ns. A PSD parameter based on photon emission time distribution (PETD) was constructed to discriminate $e^+/e^-$. Finally the application of $e^+/e^-$ discrimination in JUNO experiment was shown. It helps suppression of $^{8}\text{He}/^{9}\text{Li}$ backgrounds and improves the sensitivity by 0.6 in $\chi^2$ analysis with assumption of $\sigma = 1$ ns PMT Transit Time Spread, which will bring smearing effect to PETD.

Key words: PSD, LS, ortho-positronium

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1 Introduction

In most reactor neutrino experiments, electron antineutrinos are detected via inverse $\beta$-decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. The antineutrino signature is a coincidence between the prompt positron signal and the microseconds delayed neutron capture on target (proton or other doping isotopes). The most serious background is the cosmogenic $^{8}\text{He}/^{9}\text{Li}$ background, which can mimic the IBD signature via ($\beta^-,n$) decay. Thus, the capability of positron-electron discrimination is extremely useful to reject the $^{8}\text{He}/^{9}\text{Li}$ background.

Prior to position annihilation, it can form a neutral bound state of a positron and an electron, namely positronium. The formation threshold of positronium is 6.75 eV [1]. Depending on the total spin angular momentum, positronium is classified into spin singlet para-positronium (p-Ps) state and spin triplet ortho-positronium (o-Ps) state. In vacuum, the p-Ps state annihilates by emitting two $\gamma$ rays of 511 keV with a mean lifetime of 125 ps, while the o-Ps state emits three $\gamma$ rays with a mean lifetime of $\sim 140$ ns. In liquid scintillator (LS), the mean lifetime of o-Ps state is strongly reduced to a few nanoseconds due to the interactions of o-Ps with the surrounding medium [2]. The o-Ps in different LS solvent has slightly different lifetime and formation probability [3].

The delay of positron annihilation can induce distortion in the photon emission time distribution (PETD) of the detected photons. In addition, the two annihilation gamma rays will further induce distortion to PETD due to the Compton scattering. The PETD difference between positron and electron provides an opportunity for positron-electron discrimination in LS detector and the consequent rejection of $^{8}\text{He}/^{9}\text{Li}$ background from IBD candidates.

In this paper, we studied the potential mass hierarchy sensitivity improvement of the Jiangmen Underground Neutrino Observatory (JUNO) [4, 5] by positron-electron discrimination analysis. JUNO is a 20 kton multi-purpose liquid scintillator detector, with the primary goal to determine the neutrino mass hierarchy by detecting reactor antineutrinos. The JUNO central detector uses liner alkyl-benzene (LAB) based LS and has excellent energy resolution $\sim 3%/\sqrt{E}$. The energy scale is about 1200 photoelectron/MeV and the PMT photocathode coverage is about 78%. The outline of this manuscript is as follows. In Section 2 a newly designed apparatus for positron annihilation lifetime measurement is presented. In Section 3 the measured o-Ps lifetime in LAB is reported. Section 4 describes a pulse shape discrimination (PSD) method for positron-electron discrimination. Finally, the application of positron-electron discrimination to JUNO and the im...
improvement on mass hierarchy sensitivity is shown in Section 5.

2 Positron lifetime measurement experimental apparatus

A self-developed Positron Annihilation Lifetime Spectroscopy (PALS) was used to measure the o-Ps formation fraction and its lifetime. The schematic diagram of the experimental setup, and the electronics and data acquisition (DAQ) scheme is shown in Fig. 1.

(a) Schematic diagram of the experimental setup

(b) Electronics and data acquisition scheme

Fig. 1. Experimental apparatus

Typically the sample for the PALS is crystal or powder pressed into thin slices. To measure the positron annihilation in the LAB liquid, special design was performed. A thin positron source was made of a dried drop of liquid NaCl encapsulated in two layers of 7.5 μm Kapton films. The LS sample was full-filled in disposable Brand cuvette made of Acrylic material which is completely compatible with LS. Each cuvette has a capacity of 4.5 mL (10mm × 10mm × 45mm), and was sealed by a piece of thin Kapton film. The two cuvettes were stacked up and down with the flat positron source placed in the middle of the two films. Two opposite BaF$_2$ plastic scintillators coupled with 2-inch PMTs were covered by black film and used to measure the annihilation γ rays. The DAQ system was a fast-slow coincidence system. The fast coincidence channel was for time measurement. The BaF$_2$ crystal contains fast component with short emission time 0.6 ns and makes it suitable for time measurement. The timing signal from BaF$_2$ detector was passed to the input of a constant fraction differential discriminator (CFDD). The slow signal from the detectors, with appropriate γ-ray energy, generated the strobe signal for the time-to-amplitude converter (TAC). The analog pulse proportional to the time interval between the start and stop pulses was fed to the multichannel amplitude analyzer (MCA) and converted into a digital signal, then stored on data disk for later analysis.

3 Data taking and Data analysis

It is known that Oxygen dissolved in liquid scintillator can decrease the positron annihilation lifetime. To remove oxygen in the test sample, we bubbled the sample with high purity nitrogen for about 40 minutes. The flow rate of nitrogen was carefully controlled by a pressure reducing valve. The time interval between the 511 keV gamma from positron annihilation and 1.27 MeV gamma accompanied with sodium’s β$^+$ decay was taken as the lifetime of positron. The time resolution of the system was 190 ps (FWHM) calibrated by the two instantaneous γ rays of Cobalt-60 source.

The o-Ps lifetime was extracted from the measured lifetime spectrum using RooFit tool. Positron annihilation lifetime in LS can be described as the sum of two exponential components. The short-life p-Ps and directly annihilating positron are indistinguishable, therefore they are merged into one component. The other component represents o-Ps. Positron annihilation in the substrate material also contributes to the measured lifetime spectrum. Based on past experience, this can be described by two exponential components. The system instrumental time resolution is assumed as Gaussian distribution. The final fitting function is shown in Eq. (1), where the subscript “s” represents the contribution from source substrate materials, the σ and T are the instrumental time resolution and time latency, respectively.

\[
F(t) = \int_0^t \frac{N_s}{\sqrt{2\pi\sigma_s}} e^{-\frac{(t-t')^2}{2\sigma^2}} \left\{ (1-I_s) \times (\frac{1}{\tau_1} e^{-\frac{t}{\tau_1}} + \frac{1}{\tau_2} e^{-\frac{t}{\tau_2}}) + I_s \times (\frac{1}{\tau_1} e^{-\frac{t}{\tau_1}} + \frac{1}{\tau_2} e^{-\frac{t}{\tau_2}}) \right\} dt' \tag{1}
\]

The Life Time 9.0 program (LT9) based on the least square fitting method was used as a crosscheck. Their difference was taken as errors of the measured positron annihilation lifetime. In this measurement, optical photons were shielded by the black film and only gammas can propagate into the BaF$_2$ detector, thus in the measured lifetime spectrum there is no contribution from the LS sample’s scintillation light.

Standard sample made by Nickel was measured first, and the effects of source substrate was obtained by sub-
tracting the known lifetime spectrum of Nickel from the measured one. The positron annihilation lifetime in defectless Nickel is known to be about 108 ps [9]. The result from LT9 and RooFit is 117 ps and 112 ps, respectively. The positron annihilation lifetime spectrum in LAB is shown in Fig. (2). The top panel shows the measured and fitted lifetime spectrum with contribution from source subtracted. The bottom panel shows the residual between data and fit normalized to the statistical Poisson error of fit counts. From the unfolding result, the o-Ps lifetime is about $3.1 \pm 0.07$ ns and its formation probability is about $(43.7 \pm 1.15)$%.

Fig. 2. The measured and fitted lifetime spectra of positron annihilation in LAB.

4 Simulation and PSD performance

To exploit the difference, we created PSD parameters. Two PSD parameters were constructed to do $e^+ \text{and} e^-$ discrimination. One is the tail to total ratio in the PETD. The start of the tail was chosen to be 10 ns and the total time window was chosen to be 50 ns. The other one is the optimum Gatti parameter $[11]$ defined as Eq. (2). Here $r_i(t_n)$ denotes the photon emission probability in the time interval $t_{n-1}$ to $t_n$ for the unknown particle. The weight $w(t_n)$ was calculated using $e^+$ photon emission probability ($r_1(t_n)$) and $e^-$ photon emission probability ($r_2(t_n)$).

$$G = \sum_n r_i(t_n) w(t_n)$$

$$r_i(t_n) = \int_{t_{n-1}}^{t_n} P_i(t)dx \quad w(t_n) = \frac{r_1(t_n) - r_2(t_n)}{r_1(t_n) + r_2(t_n)}$$

Besides these two PSD parameters, an artificial neural network method was also investigated. The multi-layer perceptron algorithm, abbreviated to MLP, from ROOT Toolkit for Multivariate Data Analysis [12] was used. Such algorithm yields an output qualifier indicating the particle type. The input to the algorithm comprises 16 variables, defined as follow. We build the cumulative distribution function of the PETDs, and we set 16 thresholds equally distributed between 0.03 and 0.33. The time values at which the threshold crossings occur serve as input variables. The total number and the values of the thresholds were optimised to sample the PETD range with the most discrimination power. The training and test samples are every two other entries in the ROOT tree file.

A figure of merit (FOM) parameter was used to evaluate the PSD parameter discrepancy of positron and electron. FOM is defined as the peak distance divided by the summation of FWHM of each particle. We applied the Gatti parameter and MLP algorithm on positron and electron Monte Carlo samples, and found that Gatti parameter and MLP had similar performance. An example
is shown in Fig. 4, the electron and positron energy is 2.5 MeV, and the Gatti FOM is 0.265 and MLP FOM is 0.266. The following analysis is based on Gatti discrimination parameter.

In consideration of following studies, $e^+$/$e^-$ discrimination power at different energies was studied. The energy range extended from 1.0 MeV (the minimum deposited energy of positron) to 9.0 MeV. In this study, $\sigma = 1$ ns PMT Transit Time Spread (TTS) was added to PETD of positron and electron. The $e^+$/e$^-$ discrimination at different energy is shown in Fig. 5.

5 PSD application in JUNO experiment

The beta emitters $^8$He and $^9$Li can mimic IBD interactions by $(e^-, n)$ decays. Since the $^8$He and $^9$Li isotopes are mainly produced by the cosmic muons going through the detector, a veto on the detector volume within a time window since the last muon can be applied to reject the $^8$He/$^9$Li background. This veto strategy was studied in [3]. For example, a veto cut to reject the detector volume within a cylinder with distance from muon track less than 3 meters in a 1.2 s time window since last muon can reduce this background from 71/day to 1.6/day. However, the IBD event rate is also reduced by 17% due to the dead time caused by veto. The PSD in this study can be used as another method to reject $^8$He/$^9$Li background. With the help of the PSD method, the veto cut can be loosened to reduce the dead time without sacrificing signal to background ratio. To evaluate the improvement of the mass hierarchy sensitivity by optimizing the PSD and veto conditions, a $\chi^2$ was defined as Eq. (3). Where $i$ is the bin index of the spectra, $M_i$ is simulated spectrum including IBD signal ($S^i$) and background ($B^i$), $F^i$ is the fit spectrum with the oscillation parameters to be fitted, $\varepsilon_R, \varepsilon_r, \varepsilon_B$ are nuisance parameters corresponding to the reactor flux and detector efficiency normalization factor, reactor uncorrelated uncertainty ($\sigma_r$), and background rate uncertainty ($\sigma_B$), the spectrum shape uncertainties due to the IBD signal and background are included by introducing $\sigma_{s2b}$ and $\sigma_b$.

$$\chi^2 = \sum_{bin} \frac{(M^i - F^i)^2}{M^i + (\sigma_{s2b} S^i)^2 + \sum_b \sigma_b^2 B^i_b} + \sum_{r} (\frac{\varepsilon_r}{\sigma_r})^2 + \sum_{B} (\frac{\varepsilon_B}{\sigma_B})^2$$

$$F^i = S^i (1 + \varepsilon_R + \sum_r w_r \varepsilon_r) + \sum_b B^i_b (1 + \varepsilon_B)$$

The simulated spectrum $M^i$ is calculated assuming either normal hierarchy (NH) or inverted hierarchy (IH) without statistical fluctuations. When the fit spectrum uses the same assumption, the minimization of the $\chi^2$ over the oscillation parameters and nuisance parameters yields 0. While assuming the opposite mass hierarchy in the fit spectrum, we obtain $\chi^2_{min1}$. The sensitivity of the mass hierarchy can be expressed as $\Delta \chi^2 = \chi^2 - \chi^2_{min1}$.

The neutrino spectra after applying PSD analysis was served as the input for the $\chi^2$ analysis. The PSD cut efficiency at each energy bin of the IBD prompt and background spectrum was calculated. Since we use neutrino spectrum in the $\chi^2$ analysis, we need do a transformation between the prompt energy and neutrino energy to
get the corresponding efficiency at the neutrino spectrum bin. The conversion was done according to equation 11 in [13]. The PSD efficiencies were applied on $M^i$, $S^i$ and the specific $B^i_j$ corresponding to $^8\text{He}/^9\text{Li}$ in Eq. (3). The PSD cut efficiency errors were taken as uncorrelated systematic errors and were quadratically added to $\sigma_{b}$ and $\sigma_{b}$ in Eq. (3).

In the $\Delta\chi^2$ calculation, we scanned the PSD cut and veto conditions. The tested veto schema included combination of volume veto cylinder radius 1.6 m, 2 m, 3 m and veto time 0.7 s, 1 s, and 1.3 s. One optimized muon veto scheme that gave good $\chi^2$ was to veto the detector volume within a cylinder with distance from muon track less than 2 m in a 1.0 s time window. We can improve the $\chi^2$ from original 10.60 without PSD analysis to 11.17 after PSD analysis. The signal and background Gatti parameter distribution is shown as Fig. 6.

Fig. 6. Mixed Gatti parameter distribution

Fig. 7 shows the signal and background efficiency under the optimized Gatti parameter cut (-0.001). The cut efficiency error was estimated by carrying out the Bayesian approach, treating the number of passing events as a binomially distributed variable, with uniform prior probability assumption for the cut efficiency. The errors were enlarged 10 times to be seen clearly.

6 Conclusion

We have measured the lifetime and formation probability of ortho-positronium. In oxygen-free LAB, the o-Ps lifetime is $3.10 \pm 0.07$ ns and its formation probability is $(44.70 \pm 1.15)\%$. We solved the problem of positron vertex smearing by using kapton films and two cuvettes. The backgrounds in this design scheme was calibrated by testing standard samples.

We performed simulations under the framework SNiPER. We assumed the PMT TTS was 1 ns and the energy scale was about 1200 photoelectron/MeV, and we applied $e^+/e^-$ PSD to reduce $^8\text{He}/^9\text{Li}$ backgrounds. From the MH sensitivity study, by loosening the muon veto cut and instead using PSD analysis to reject the $^8\text{He}/^9\text{Li}$ backgrounds, $\chi^2$ improvements can be made. For example, veto the detector volume within 2 meters in a 1.0 s time window can improve the final $\chi^2$ from 10.60 (w/o PSD) to 11.06 (w/PSD).

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