Normalization Studies on the 2016-2018 Data for the KOTO Experiment

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Abstract. The KOTO experiment is searching for the rare decay of the neutral kaon, $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$. KOTO collected data from 2016 to 2018 and accumulated $3.1 \times 10^{19}$ Protons on Target (POT). Results on the normalization analysis of this dataset are described. Three normalization modes, $K_L^0 \rightarrow 3\pi^0$, $K_L^0 \rightarrow 2\pi^0$, and $K_L^0 \rightarrow 2\gamma$, are used to calculate the $K_L^0$ flux and the number of kaons at the beam exit. The data is well reproduced by the Monte Carlo and the total number of kaons is $(7.14 \pm 0.05) \times 10^{12}$. This gives a Single Event Sensitivity (SES) of $6.9 \times 10^{-10}$.

1. Introduction
The KOTO experiment at the J-PARC research facility in Tokai, Japan aims to observe and measure the rare decay of the neutral kaon, $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$. This decay has a Standard Model (SM) predicted branching ratio (BR) of $(3.00 \pm 0.30) \times 10^{-11}$ [1]. While this process is extremely rare, it is a good probe to test for new physics beyond the SM due to small theoretical uncertainties. The current best experimental upper limit is $< 3.0 \times 10^{-9}$ at the 90% C.L, which was set by KOTO in 2019, from data that was collected in 2015 [2]. This improved the previous upper limit set by the E391a collaboration [3] by an order of magnitude.

2. Experimental Method
KOTO is a fixed target experiment in which a 30 GeV beam of protons collides with a stationary gold target from which a highly collimated, neutral beam of kaons is produced. The kaons from the secondary beam decay within the decay region inside the KOTO detectors which consist of scintillating veto detectors and a Cesium Iodide (CsI) calorimeter (Figure 1). The signal decay is two photons from the pion which hit the CsI calorimeter and the two neutrinos are not seen by the KOTO detectors. The strategy of KOTO is to observe the two photons from the $\pi^0$ decay with no other particles present in the detectors, in which the two photons have a discernible, large, transverse momentum.

3. 2016-2018 Data
After taking data in 2015, a new inner barrel (IB) detector was installed and improvements on the trigger and data analysis techniques were made. From 2016 to 2018, KOTO collected a total of $3.1 \times 10^{19}$ POT, which is about 1.5× more data than was collected during 2015. The analysis
4. Normalization Analysis

There are three variables needed in order to calculate the branching ratio (Equation 1): the number of reconstructed \( K^0_s \rightarrow \pi^0 \nu \bar{\nu} \) events \( (N_{signal}) \), the number of kaons generated at the beam exit \( (N_{K^0_L}) \), as well as the acceptance of the signal mode \( (A_{signal}) \).

\[
BR(K^0_L \rightarrow \pi^0 \nu \bar{\nu}) = \frac{N_{signal}}{N_{K^0_L} \times A_{signal}}
\]

The Single Event Sensitivity (SES) is a measure of how sensitive we are to observe a signal event,

\[
SES = \frac{1}{N_{K^0_L} \times A_{signal}}.
\]

We use three “normalization modes”, \( K^0_L \rightarrow 3\pi^0 \), \( K^0_L \rightarrow 2\pi^0 \), and \( K^0_L \rightarrow 2\gamma \), to estimate the number of kaons at the beam exit \( (N_{K^0_L}) \). We use these modes because they are easily reconstructed in the KOTO detectors and have a high branching ratio relative to the signal decay. Calculating the number of kaons generated at the beam exit requires knowing what the flux of \( K^0_L \)s is into the detector. The flux is defined as,

\[
K^0_L \text{ flux} = \frac{K^0_L \text{ yield}}{\text{POT}_{\text{runs}}/\text{POT}_{\text{norm factor}}}
\]

where \( \text{POT}_{\text{norm factor}} \) is the J-PARC design value for the number of protons on target per spill and is \( 2 \times 10^{14} \). \( \text{POT}_{\text{runs}} \) is the number of protons on target (POT) divided by the normalization prescale, which is 30. The \( K^0_L \) yield is calculated separately for 6, 4, and 2 cluster events as

\[
K^0_L \text{ yield} = \frac{N_{data}}{A_{total}}
\]

where \( N_{data} \) is the number of events with a certain number of clusters in data that remain after applying all kinematic and veto cuts, and \( A_{total} \) is the total acceptance which is a sum of the acceptance for each mode multiplied by the branching ratio for that mode. The total acceptance is based on the Monte Carlo and for a particular mode, includes the contamination from the
other two modes when the Monte Carlo is sorted into either 6, 4, or 2 cluster events. The yield and flux are calculated separately for each mode and then multiplied by the total number of POT to get the number of kaons generated at the beam exit:

$$N_{K_L^0} = \frac{K_L^0 \text{ flux}}{\text{POT norm factor}} \times \text{POT}$$

(5)

The $K_L^0 \rightarrow 2\pi^0$ mode is used in the final evaluation of the total number of kaons because it has an energy profile closest to the energy profile of the signal. The total number of kaons calculated for the 2016-2018 data set is $(7.14 \pm 0.05) \times 10^{12}$.

Along with calculating the number of kaons generated at the beam exit, these modes are also used to evaluate the kinematic and veto cut efficiencies and check the Monte Carlo reproducibility of the data. Figure 2 shows kinematic distributions for each normalization mode and there is good agreement between data and Monte Carlo. The last variable in the branching ratio calculation, the signal acceptance ($A_{\text{signal}}$), includes the geometric acceptance of the detectors and the kinematic and veto efficiencies for the cuts made on the data.

Figure 2: Kinematic distributions for $K_L^0 \rightarrow 3\pi^0$ (red), $K_L^0 \rightarrow 2\pi^0$ (blue), and $K_L^0 \rightarrow 2\gamma$ (green).
5. Summary
The KOTO experiment took data from 2016 through 2018 and collected a total of \((7.14 \pm 0.05) \times 10^{12}\) number of kaons which is 1.57\times more than the number of kaons collected in 2015. The number of protons on target (POT) collected in this data set was \(3.1 \times 10^{10}\) and is 1.5\times more than the amount collected in 2015. The estimated Single Event Sensitivity (SES) is \(6.9 \times 10^{-10}\).

6. Acknowledgements
This work is supported by the U.S Department of Energy, Office of Science, under research award No.s DE-SC0007859, DE-SC0006497, and DE-SC0009798.

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