APPLICATION OF MULTIVARIATE ANALYSIS IN SEARCH OF THE $K_S \to 3\pi^0$ DECAY IN THE KLOE EXPERIMENT*

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According to the Standard Model, one of the purely CP-violating process is the never observed $K_S \to 3\pi^0$ decay. The best upper limit on the branching ratio of this process $\mathrm{BR}(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ was obtained in the KLOE experiment using cut-based analysis. In this paper, we show preliminary results of an alternative approach to those studies using multivariate analysis methods.

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1. Introduction

CP violation was discovered for the first time in 1964 during the studies of neutral K mesons decays ($K_L \to 2\pi^0$) by Christenson, Cronin, Turlay and Fitch [1, 2]. Later, in 1967, this violation was also discovered in the semileptonic K_L decays [3]. The theoretical model explaining the CP breaking was provided in 1973 by Kobayashi and Maskawa, who concluded that if there were at least six quark flavours, this symmetry would not hold. At present, most of the experiments studying discrete symmetries are focused on the neutral B- and D-meson systems. However, there are still several open issuses in the kaon physics connected with the CP violation such as, for example, decay of K_S to 3π [4].

The present knowledge about this decay is poor mainly due to very low decay rates. The best upper limit on the branching ratio of this process $\mathrm{BR}(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ was measured with the KLOE detector operating at the DAΦNE collider located in the Italian National Institute of Nuclear Physics in Frascati [5]. At the same time, predictions based on the Standard Model give $\mathrm{BR}(K_S \to 3\pi^0) \sim 2 \times 10^{-9}$, which is one order of magnitude smaller than the measured upper limit [4].

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2. The KLOE detector

The KLOE (K-long Experiment) detector operated at the DAΦNE (Double Annular ϕ-factory for Nice Experiments) e^+e^- collider. It consisted mainly of a cylindrical drift chamber (DC) and an electromagnetic calorimeter (EMC). They were surrounded by a superconducting coil which provided a 0.52 T magnetic field and by an iron yoke.

The 3.3 m long cylindrical DC, with 2 m radius, was constructed out of carbon fiber composite and was filled with a gas mixture of helium (90%) and isobutane (10%). It operated in the all-stereo geometry providing tracking in three dimensions with resolutions of $\sigma_{xy} \sim 200$ μm and $\sigma_z \sim 2$ mm and determining particle's momentum with an accuracy of 0.4% [2, 4, 6].

The 4.3 m long barrel-shape EMC with two lead-scintillating fibers endcaps covered 98% of the solid angle. It allowed for measurments of particle flight time and energies with accuracies of $\sigma_T = 0.057 \text{ ns}/\sqrt{E(\text{GeV})} \oplus 0.1$ ns and $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$, respectively [2, 4, 6, 7].

3. Search of the $K_S \to 3\pi^0$ decay

The experimental signature of the decay of interest are 6 gamma quantas coming from the interaction point (due to a very short lifetime of the ϕ and π^0 mesons) together with a registration of a K_L meson in the calorimeter (so-called K_L-crash). K_L has an average velocity of around $\beta = 0.21$ and is delayed in relation to the products of the K_S decay. Therefore, it is identified as a particle with a correspondingly large deposited energy and proper velocity [2, 4].

3.1. Determination of the background — preselection

The main background to the searched decay originates from the $K_S \to 2\pi^0$ events which are reconstructed as six photon events due to the fragmentation of the electromagnetic showers or the accidental coincidence between the ϕ decay event and the DAΦNE background [2, 4]. Good understanding of this process is important to increase the efficiency of background reduction. For this reason, a targeted studies described in [2] were performed. In order to validate and tune Monte Carlo simulation to experimental data, determination of the probability of electromagnetic showers fragmentation and coincidences with machine background were carried out using a dedicated probabilistic model developed in [8].

Moreover, background events were categorized into 3 groups: events with two splitted clusters, events with two accidental clusters or one accidental and one splitted cluster, events originating in other processes ($\phi \to K^+K^-$ or $\phi \to \pi^+\pi^-\pi^0$). Next, simulated Monte Carlo events were fitted to the data giving scaling factors [2].

Reduction of the background was also provided by rejecting events with low deposited energy of the interacting K_L mesons $E_\mathrm{cr} > 150$ MeV and making a restriction on the velocity of the tagging K_L meson: $0.2 \leq \beta_\mathrm{cr} \leq 0.225$.

3.2. Cut-based analysis

Further analysis was aimed at extracting $K_\mathrm{S} \to 3\pi^0$ events from the background left after preselection. For this purpose, five variables were defined:

— χ^2 of a kinematic fit
It was performed with the following conditions: K_S mass, total 4-momentum conservation, consistency between the measured time and position of each cluster [2];

— $\Delta E/\sigma_E = E_{K_\mathrm{S}} - \sum E_\gamma/\sigma_E$
A variable expressing the consistency between the K_S energy reconstructed by tagging and the sum of energies of the four gamma quanta best fulfilling the $2\pi^0$ hypothesis normalized to the K_S mass resolution [2];

— $\chi^2_{2\pi}$
χ^2-like variable expressing the probability that the registered event is the $K_\mathrm{S} \to 2\pi^0$ decay with additional accidental or splitted clusters [2];

— $\chi^2_{3\pi}$
Parameter showing how much the event fulfills the $3\pi^0$ hypothesis [2];

— R_min
The minimum distance between clusters.

The motivation for using those parameters and their exact formulas are described in detail in [2]. As the result of the optimalization of cuts on these variables, the signal efficiency of $K_\mathrm{S} \to 3\pi^0$ decay was estimated to be $\epsilon_{3\pi^0} = 0.233 \pm 0.012_\mathrm{stat}$. The corresponding number of signal candidates and background estimation amounted to 0 [2].

3.3. Multivariate analysis (MVA)

As an alternative to the cut-based analysis, multivariate analysis was carried out. First, the same preselection of the data was made and one addictional cut on parameter $R_\mathrm{min} > 65$ cm giving a $\sim 25\%$ reduction of the background with more than 86% of signal efficiency. Then, we have used the multilayer perceptron (MLP) neural network built into the ROOT data analysis package [9]. It consisted of four input neurons, one hidden layer with four neurons and one output neuron. Stochastic minimization was chosen as the learning method. The MLP network was trained with 110818 MC background events and 507 MC signal events [4]. Each input neuron corresponded to one of four parameters: χ^2, $\Delta E/\sigma_E$, $\chi^2_{2\pi}$, $\chi^2_{3\pi}$.

Preliminary results show that cutting on the neural network output parameter which entirely reduces the MC background sample corresponds to signal efficiency equal to $\epsilon_{3\pi^0} \sim 18\%$. Application of the neural network on the experimental data sample revealed that cutting on neural network parameter which retains no data events gives signal efficiency $\epsilon_{3\pi^0} \sim 21\%$ [4].

4. Conclusions and outlook

We have performed studies of using alternative multivariate analysis approach to search for the $K_S \to 3\pi^0$ decay with the KLOE data. The research was done using the same data as for the cut-based analysis. The best, so far, performance of the analysis gave signal efficiency corresponding to complete reduction of MC background equal to $\epsilon_{3\pi^0} \sim 18\%$ and corresponding to complete reduction of the data equal to $\epsilon_{3\pi^0} \sim 21\%$ [4]. The old cut-based analysis resulted in the same background reduction factor with the efficiency for the signal of about 23% [2]. Thus, one can conclude, that the obtained results are comparable to the cut-based analysis [2], showing a possibility of successful application of this method.

Presented MVA analysis is planned to be used in the new search for the $K_S \to 3\pi^0$ decay with the KLOE-2 data, either as a standalone analysis or as a supplementary method to efficiently reduce the background.

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