Mixing MC events in a reactor neutrino experiment *

ZHANG Yi-Chun(张一纯)[1;1)] CHEN Xiao-Su(陈晓苏)[2] HE Miao(何苗)[2]
HUANG Xing-Tao(黄性涛)[3] WANG Meng(王萌)[3] LI Wei-Dong(李卫东)[2] ZHANG Zi-Ping(张子平)[1]

[1] University of Science and Technology of China, Hefei 230022, China
[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[3] Shandong University, Jinan 250100, China

Abstract: In reactor neutrino experiments, the analysis of time correlations between different physical events is an important task. Such analysis can help to understand the physical mechanisms of the signal and background events as well as the details of event selection and background estimation. This study investigates a "sampling and mixing" method used for producing large MC data samples for the Daya Bay reactor neutrino experiment. We designed a simple, generic mixing algorithm and generated large MC data samples for physics analysis from several samples according to their respective event rates. Basic plots based on the mixed data are shown.

Key words: reactor physics experiments, time correlation, sampling and mixing, event rates

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1 Introduction

The Daya Bay reactor neutrino experiment is designed to measure the neutrino mixing angle θ_{13} with a sensitivity better than 0.01 for $\sin^2 2\theta_{13}$ [1].

There are three sites (DYB site, LingAo site and Far site) in the Daya Bay reactor neutrino experiment to reduce the systematic errors. Each site has an experimental hall surrounded by enough rocks which can make the cosmic rays decrease. In the experimental halls on the DYB site and LingAo site there are five sub-detector modules: two antineutrino detectors (AD1, AD2) surrounded by an inner water shield and an outer water shield (IWS, OWS) and resistive plate chambers (RPC). In the experimental hall on the Far site, there are seven sub-detector modules: including another two antineutrino detectors (AD3，AD4). ADs are used to detect antineutrinos from the nuclear reactors while WSs and RPCs are used to tag muons from cosmic rays. At each Daya Bay experimental site, data collection will produce three types of data flow by ADs, WSs and RPC separately. After mixing these data flows, the Daya Bay real data will contain time ordered events mainly consisting of Inverse Beta Decay (IBD), cosmic muons, natural radiation, muon induced neutrons and radioactive isotopes.

To get the MC data of DYB site, the detector simulation and digitalization of these sub-detector modules should be finished. These simulation components mainly measure the deposited energy of the particles. The time information between different kinematic events in the MC data needs to be constructed by an extra component called "events mixing". By this component, the different simulated physical samples (such as muons, radioactivities) could be reused, resulting in the saving of lots of CPU time in simulation. In addition, the rates of physical samples could also be changed easily when using the mixing method in MC-Tuning. So, this method has been one important step for physical MC data production.

The off-line software system (NUWA) [2] of the Daya Bay reactor neutrino experiment is a data processing software platform based on the Gaudi framework [3], in which one can do simulation, calibration, reconstruction and physics analysis. The data mixing service to produce large MC data samples has been developed on this platform. This service encapsulates the complicated mixing processing to enable users to generate specific physical MC data according to their analysis requirements. It hides the complex structure of the data model in the files and supplies unified interfaces.

2 The properties of MC data in the Daya Bay experiment

The properties of data structure in reactor experiments are different from those in collider experiments. The time correlation between two successive events plays

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1) E-mail: yczhang@mail.ihep.ac.cn

an important role. So, constructing the time correlation during the production of MC data becomes crucial. Generating data with a time correlation can also help to understand the physical mechanism of the signal and background events, to apply events discrimination, and to develop algorithms for physics analysis.

The time correlation in the MC data can be of two types. Some kinematic events (such as cosmic muon) can cause several electronics signals (PMT or RPC readout) in one or more detectors. The time correlation between the different readouts originating from the same kinematic event is the first type and the time correlation between two successive kinematic events is the second type. The second type of time correlation is relevant to the event rates of different kinds of samples, while the first one has a strong relationship with physics processes in detectors and digitalization, which determined the design of the software data model.

In the NUWA framework, the standard MC data simulation includes detector simulation and digitalization. Each stage of the simulation has dedicated data models for the storage of the simulation results. However, these data models are the same for different physics processes and so do the interfaces of accessing these data in other algorithms.

Figure 1 shows the standard process of MC simulation in the NUWA framework. One entire kinematic event is generated by inputting one generator into the detector simulation module. After digitalization, one or more readout can be obtained. The first kind of time correlation of these readouts in one kinematic event is kept by the their own trigger time set automatically in digitalization.

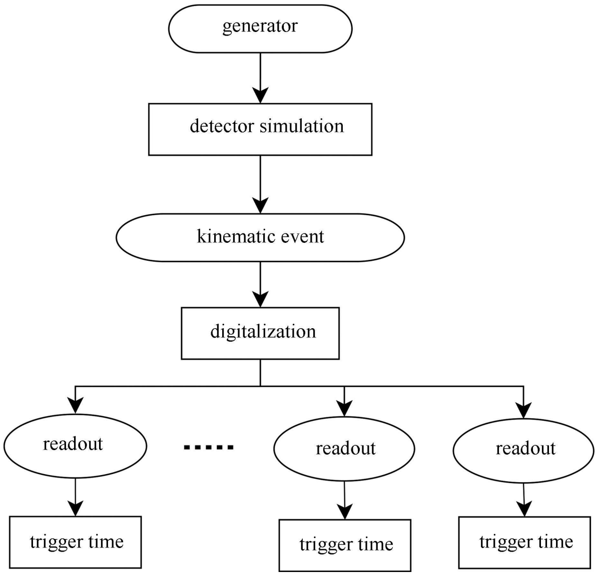

Fig. 1. Process of simulation of one kinematic event in NUWA. The arrows indicate the order of the segments in simulation.

Since the standard simulation modules construct only the first kind of time correlation, the time interval between two successive kinematic events has no meaning in physics. Therefore, a dedicated method has to be added to construct the second kind of time correlation.

3 The mixing method and its implementation

As described above, the second kind of time correlation needs to be constructed independently from the detector simulation and digitization.

In the Daya Bay reactor neutrino experiment, signal events from inverse beta decay (IBD) are used for the calculation of the mixing angle $\sin^2 2\theta_{13}$. But the event rates of natural radioactivity and cosmic muons are much higher than those of IBD. The events from natural radioactivity and cosmic muons contribute to the correlated and uncorrelated backgrounds with lower event rates than the IBD events. In addition, the simulation of cosmic muons will cost lots of CPU time. Therefore, physical samples except for IBD events could be re-sampled when mixing all the samples, which can reduce the CPU time for simulation and save disk space.

3.1 Definition and determination of event rates

3.1.1 Properties of time structure

In one certain kind of physics sample (neutrino, cosmic muon or natural radioactivities) with event rate λ, each kinematic event is independent from the others (the Poisson process). So, within a certain time window, the number of kinematic events follows the Poisson distribution while the time interval between two successive kinematic events follows exponential distribution [4]:

$$P(t)=\frac{1}{\tau}\exp\frac{-t}{\tau}, \tag{1}$$

where the time constant τ is the average time interval. The event rate λ and time constant τ satisfy $\lambda\tau=1$.

As for neutrons and isotopes with a long lifetime generated by cosmic muon, the time correlation between them and the original muon belongs to the first type of time correlation and is determined automatically by simulation. In muon samples, these events and their original muon are combined as one kinematic event.

Suppose that there are two physical samples: A and B with time constants τ_A and τ_B, respectively. After mixing these two samples according to their corresponding exponential distributions, the time interval between two successive events in the mixed sample M still follows exponential distribution. The mixed time constant τ_M can be calculated by

$$\frac{1}{\tau_M}=\frac{1}{\tau_A}+\frac{1}{\tau_B}. \tag{2}$$

Equation (2) can be extended to the situation with n physical samples as follows:

$$\frac{1}{\tau_{\mathrm{M}}}=\sum_{i}\frac{1}{\tau_i}, \tag{3}$$

where τ_i is the event rate of i-th sample. The mixed event rate λ_{M} and mixed time constant τ_{M} still satisfy the reciprocal relationship.

3.1.2 Event rates of main physical samples in the Daya Bay reactor neutrino experiment

The physical samples needed for the Daya Bay reactor neutrino experiment are mainly IBD, natural radioactivity, cosmic muons as well as muon-induced neutrons and radioactive isotopes (cosmogenic isotopes). Before mixing them, the event rates of these samples should be determined.

Most important is that the event rate of inverse beta-decay events can be calculated straightforwardly based on the knowledge of the reactors. From the other reactor neutrino experiments, the IBD event rate n_{ν} is estimated below as [5]:

$$n_{\nu}(E_{\nu})=\frac{\sigma_{\mathrm{IBD}}(E_{\nu})N_{\mathrm{p}}\varepsilon}{4\pi R^2}\frac{W_{\mathrm{th}}}{\langle E_{\mathrm{f}}\rangle}\sum_{i}\alpha_i S_i(E_{\nu}) \tag{4}$$

In Eq. (4), E_{ν} is the energy of antineutrinos emitted from the reactor cores, $\sigma_{\mathrm{IBD}}(E_{\nu})$ is the cross section of the inverse beta decay in ADs, N_{p} is the number of target protons, ε is the efficiency of neutron detection, R is the distance from reactor core to detector, W_{th} is the thermal power of the reactor, $\langle E_{\mathrm{f}}\rangle$ is the average energy per fission absorbed in the reactor core, α_i is the composition of i-th fuel, obtained from the reactor simulation, $S_i(E_{\nu})$ is the normalized energy spectrum of antineutrino by the i-th fuel. The estimated results are shown in Table 1.

Table 1. The inverse beta decay event rate in each site of the Daya Bay reactor neutrino experiment.

site	$\lambda/(/\mathrm{day})$	τ/s
DYB site	930	93
LingAo site	760	110
far site	90	960

In order to study the muon veto and muon-induced spallation neutrons and cosmogenic isotopes through a mixed MC sample, the angular distribution and flux of muons from cosmic rays in each experimental site should be investigated carefully by simulation. The standard Gaisser formula [6] has been modified based on the data from the measurement of cosmic rays on the sites to describe the muons flux.

Using the profile data of mountains around the sites, the cosmic muons transported from the atmosphere to the underground detector sites are simulated using the MUSIC package by Geant4 [7], which will give the detector responses to muons in the sub-detector modules in the experimental hall as shown in Table 2.

Table 2. The muon event rate on each experimental site. Muons are the ones crossing the water shield theoretically. Taggable neutrons mean those with parent muons may be detected by the muon system, whereas rock neutrons coming from muons have no chance to be detected. Except $^{8}\mathrm{He}/^{9}\mathrm{Li}$, cosmogenic isotope rates are counted for beta decay with an energy greater than 6 MeV.

event type	DYB site $\lambda/(/\mathrm{day})$	LingAo site $\lambda/(/\mathrm{day})$	far site $\lambda/(/\mathrm{day})$
muons	3.1×10^{7}	1.9×10^{7}	1.0×10^{6}
taggable neutrons	5.0×10^{2}	3.3×10^{2}	4.7×10^{1}
rock neutrons	6.5	4.4	4.2×10^{-1}
$^{8}\mathrm{He}+{}^{9}\mathrm{Li}$	3.7	2.5	2.6×10^{-1}
$^{12}\mathrm{B}+{}^{12}\mathrm{N}$	3.96×10^{2}	2.67×10^{2}	2.75×10^{1}
$^{9}\mathrm{C}$	1.66×10^{1}	1.12×10^{1}	1.15
$^{8}\mathrm{B}$	2.45×10^{1}	1.65×10^{1}	1.71
$^{8}\mathrm{Li}$	1.39×10^{1}	9.3	9.6×10^{1}

At last, there are still various natural radioactivity sources in this experiment. Those mainly comprise$^{238}\mathrm{U}/^{232}\mathrm{Th}/^{40}\mathrm{K}$ in rocks around the experimental halls, the water shield, the PMT glass, Gd-liquid scintillator/liquid scintillator, weld rods and materials used in the ADs, $^{60}\mathrm{Co}$ in the detector vessel and other supporting structures, $^{222}\mathrm{Rn}/^{85}\mathrm{Kr}$ in air, dust and other impurities. From simulation and measurement, the event rate of natural radioactivity can be obtained, as shown in Table 3.

Table 3. Natural radiation rates. 1 MeV cut on visible energy in detector has been applied.

natural radioation	$\lambda/(/\mathrm{day})$	τ/s
in rocks	3.0×10^{5}	0.29
in water shield	7.3×10^{5}	0.12
in stainless steel vessel	1.6×10^{6}	0.057
in PMT glass	6.7×10^{5}	0.13
in Gd-LS	6.9×10^{4}	1.3

3.2 Mixing service and algorithm based on EvtSelector mechanism

NUWA is an off-line framework based on Gaudi, in which object oriented technologies have been used throughout. It also supports event data processing applications that run in different processing environments. In this framework, data and algorithms have been separated and one can use a “Service” module and an “Algorithm” module to manipulate the data. A Transient Event Store (TES) mechanism is used in the “evnet cycle” controlled by another module called the “EvtSelector” [8]. In the mixing task, three modules (MixRootEvtSelector, MixRootIOCnvSvc and MixingAlgorithm) work with each other to complete this work, as shown in Fig. 2.

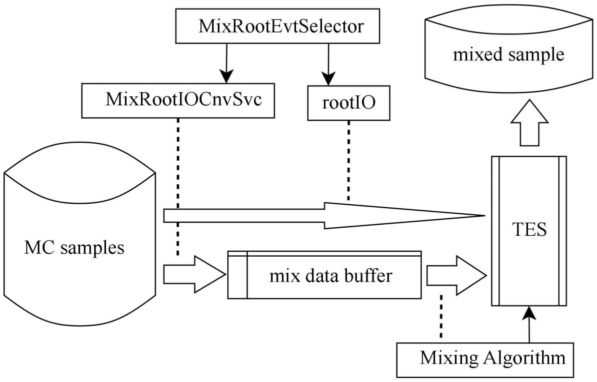

Fig. 2. Data flow during mixing with the software modules. The hollow arrows indicate the direction of data flow. The dashed lines connect each data flow with its host software module. The arrows show the relationship between one module and its sub-modules.

MixRootIOCnvSvc is a Gaudi service invoked by MixRootEvtSelector [9]. At the initialization stage of the mixing task, this service loads the types and event rates of samples being mixed, sets the beginning time, samples the beginning event of each sample, and calculates τ_{M}, the average time interval between two successive events in the mixed sample by Eq. (3).

In every execution cycle, MixRootIOCnvSvc will choose one sample randomly according to the event rate of each sample, and read in one kinematic event. At the same time, this service also generates a time interval randomly according to the exponential distribution with time constant τ_{M}, as the time interval between a current kinematic event and that in the last cycle.

The kinematic event read in will be resolved in this service by a kernel algorithm, presenting several time-ordered readouts, which will be cached in an inner mixed data buffer. Subsequently, the earliest readout in the buffer will be transported to MixingAlgorithm, while MixRootEvtSeletor keeps extra tags of this earliest readout, including the name of the sample this readout comes from and the kinematic event entry of this readout.

The MixRootEvtSelector sends these tags to the standard I/O module called RootIO. RootIO will then load the MC-truth information (generator, tracks and vertices) into TES according to tags it received.

On the other hand, MixingAlgorithm will associate the MC-truth information in TES with the readout it received and then output them into the mixed file. These mixed files containing readouts with MC-truth information instead of kinematic events, are very similar to the real data files just containing readouts.

MixRootIOCnvSvc, MixRootEvtSelector and MixingAlgorithm are packed in one package called "Mixing" as a CMT [10] package in NuWa.

4 Validation of mixed data

Before producing large mixed data, the mixing package should be tested. Eq. (2) provides a simple method to do this task. Gamma events and positron events are simulated separately, and then these two samples are mixed though the mixing method according to their respective event rates $\tau_{\mathrm{gamma}}=4.32$ and $\tau_{\mathrm{positron}}=2.16$ s. By Eq. (2), the theoretical value of τ_{M}=1.44 s can be obtained easily.

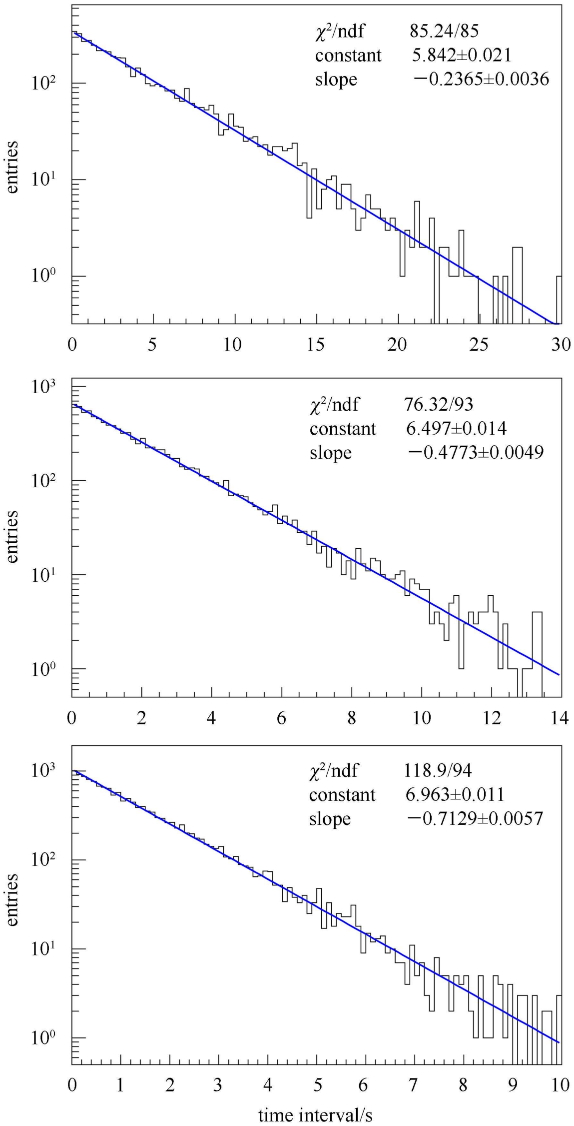

Fig. 3. Different time interval distributions in the mixed data. The upper figure shows the time interval of gamma events in mixed data with fitted value τ_{fg}=4.23 s, the middle figure shows the time interval of positron events in mixed data with fitted value τ_{fp}=2.10 s, the lower figure shows the time interval of mixed events with fitted value τ_{fM}=1.40 s. All of the results are very close to the theoretical values.

From the mixed data, gamma events and positron events can be selected based on MC-truth information with the distributions of their own time intervals. The distribution of time interval of the mixed events can be accessed directly. After fitting the histograms by exponential function, the results can be compared with the theoretical values to check if those samples are mixed according to their own event rates. The results are shown in Fig. 3.

Three months' MC data for the Daya Bay reactor neutrino experiment have also been produced by simulation and mixing. These data could be used to do some physical analysis, such as IBD-event selection and investigation of neutron multiplicity. In this paper, basic results from the mixed data are shown. The energy spectrum of all triggers in the antineutrino detectors are shown in Fig. 4. Neutron capture time distributions of IBD-events in Gd-LS after selection are shown in Fig. 5.

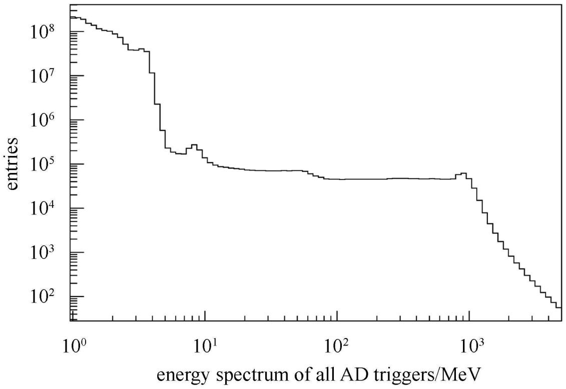

Fig. 4. The energy spectrum of triggers with energy $E>1.0$ MeV in antineutrino detectors. Those events with energy lower than 6 MeV are mostly natural radioactivities. Neutrons from both cosmic muons and inverse beta decay are captured by Gadolinium nuclei in Gd-doped liquid scintillator to form the small peak around 8 MeV. Another small peak around 1 GeV indicates cosmic muons.

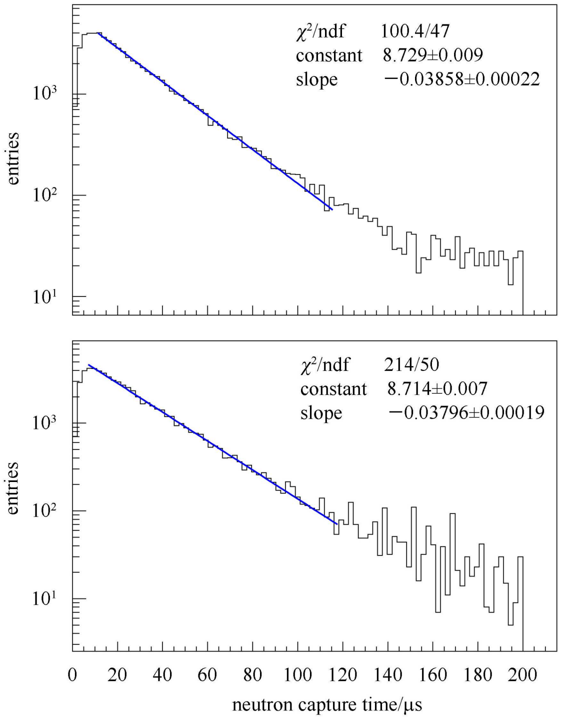

Fig. 5. Distribution of neutron capture time in Gd-LS. The upper plot shows the result in AD1 while the lower one shows the result in AD2. Neutrons are thermalized during their first 10 μs of existence in the detector central volume. Thus for time longer than 10 μs, the neutron capture events will exhibit an exponential time constant. The fitting range is [10 μs, 120 μs] just to see the exponential process of neutron capture in Gd-LS more clearly. The plateau between 140 μs and 200 μs is due to the accidental coincidences.

5 Conclusion

Event mixing method and its software implementation have been validated in practical applications. The method can also be used as a tool for physics analysis when different mixing strategies are applied. Further investigations and applications are in progress.

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