The Muon System of the Daya Bay Reactor Antineutrino Experiment

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Abstract

The Daya Bay experiment consists of functionally identical antineutrino detectors immersed in pools of ultrapure water in three well-separated underground experimental halls near two nuclear reactor complexes. These pools serve both as shields against natural, low-energy radiation, and as water Cherenkov detectors that efficiently detect cosmic muons using arrays of photomultiplier tubes. Each pool is covered by a plane of resistive plate chambers as an additional means of detecting muons. Design, construction, operation, and performance of these muon detectors are described.

94 *Keywords:* Neutrinos, Water Shield, Cosmic ray, Muons, Underground

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96 1. Introduction

97 The Daya Bay Reactor Antineutrino Experiment is designed to determine
 98 the last unknown neutrino mixing angle θ_{13} by observing antineutrino oscilla-
 99 tions, with the quantity $\sin^2 2\theta_{13}$ measured to a precision of 0.01 or smaller [1].
 100 The heart of the Daya Bay experiment is its set of eight functionally identical
 101 antineutrino detectors (ADs) [2], distributed amongst three experimental halls
 102 located underground to suppress the cosmic muon flux. Six reactor cores at
 103 the nearby Daya Bay and Ling Ao reactor complexes provide a total thermal
 104 power of 17.4 GW. Two experimental halls close to the reactor cores measure
 105 the mostly unoscillated antineutrino spectrum, while a third experimental hall
 106 at a baseline of about 2 km measures the spectrum near the θ_{13} oscillation max-
 107 imum (Fig. 1). From surveys of the mountain profile and granite cores, which
 108 determined the bulk density to be about 2600 kg/m³, the overburden is 860
 109 meters-water-equivalent (mwe) at the far hall, and 250 mwe and 265 mwe at the
 110 near halls.

111 Antineutrinos are detected in the ADs via the inverse beta decay (IBD)
 112 interaction [3, 4] $\bar{\nu}_e p \rightarrow e^+ n$. The IBD signature is a coincidence between the
 113 prompt energy deposit from the positron and the delayed release of an 8 MeV
 114 γ cascade from neutron capture on gadolinium [5, 6]. The delay occurs while

Figure 1: Layout of the experimental halls and reactor cores. The reactor cores are indicated by black circles. The near experimental halls are the Daya Bay hall (EH1) and the Ling Ao hall (EH2). The far hall is EH3.

the neutron thermalizes, with a mean time to capture of about $30 \mu\text{s}$.

The *raison d'être* for the Daya Bay Muon System is to prevent (as a passive shield) and to eliminate (as an offline veto) nearly all IBD candidates that are not actually reactor antineutrino captures in an AD. To this end, the ADs in each hall are immersed in a pool of ultrapure water which shields the ADs from radioactivity of the surrounding rock and other materials. The pools are instrumented with photomultiplier tubes (PMTs) to serve as water Cherenkov detectors, tagging muons that can produce cosmogenic backgrounds such as fast neutrons, ^9Li , and ^8He .

Each near hall houses two ADs (Fig. 2), and the far hall houses four. A Tyvek[®] optical barrier divides each pool into inner and outer water shields (IWS & OWS), both populated with PMTs as shown in Table 1. The OWS comprises the outer 1 m of each pool's sides and bottom (but not the top – the IWS extends all the way to the surface). At least 2.5 m of water shields each AD from every direction, reducing the expected AD PMT rate from rock

Figure 2: Near hall configuration showing two ADs in a pool, one in cross section. The near hall pools are 16 m long by 10 m wide. The far hall pool houses four ADs and is 16 m long by 16 m wide. The pools are all 10 m deep. An optical barrier made of Tyvek divides the pool into inner and outer water shields.

radioactivity by a factor of about 10^6 , to less than 50 Hz in each hall. The expected neutron rate per day (summed over all ADs in a hall) is 18 in EH1, 12 in EH2, and 1.5 in EH3.

An array of RPCs covers each pool, extending about 1 m beyond the pool on each side. The RPCs detect about one third of the muons which miss the pool but which are still close enough to contribute fast neutron and other cosmogenic backgrounds to the IBD signal.

2. The water shield and muon detector

2.1. Water

The Daya Bay design specifies water with an attenuation length of at least 30 m for wavelengths near 420 nm and less than 5 Bq/m³ of radon. The water system consists of a dedicated polishing station in each of the three halls, which delivers ultrapure water to its pool at a resistivity of 18 MΩ-cm and less than

Table 1: Muon PMT population. The IWS PMTs all face inward (towards the ADs), while some OWS PMTs face outward.

Hall IWS	OWS (inward/outward)	Total
EH1 121	167 (103/64)	288
EH2 121	167 (103/64)	288
EH3 160	224 (128/96)	384

10 ppb O₂, at a flow rate of 5 m³/hr at the near halls (small pools) and 8 m³/hr at the far hall (large pool) [7]. Located centrally to the three experimental halls is a station that pre-treats water from the civil water supply and feeds the three halls during filling and as needed after filling to maintain constant levels in the pools.

A comprehensive program was developed to test all candidate materials for compatibility with ultrapure water, to ensure that nothing that would significantly degrade the water was allowed into the pools. As part of this program, a small prototype detector was constructed at the Institute for High Energy Physics, Beijing (IHEP) with a circulation and purification system capable of producing water with an attenuation length of 80 m near 420 nm [8]. This prototype system guided the design of the water system for Daya Bay.

The sub-tropical climate at Daya Bay required the water system to cool the water. This need was confirmed by measurements of the underground rock temperature (27-28 C), and reports that the water source was a shallow surface pool which, in the long Daya Bay summer, could reach temperatures of 35 C and perhaps even warmer. As a compromise between lower noise rates in the AD PMTs for cooler temperatures and the cost of greater cooling capacity, the cooling capacity was designed to maintain a water temperature of 24 C, maintained to within less than 1 C.

163 *2.2. Photomultiplier Tubes*

164 The pools are instrumented with two types of pressure-resistant 20 cm hemi-
165 spherical PMTs, powered by CAEN 48-channel A1932AP modules housed in SY
166 1527LC mainframes.

167 Newly purchased from Hamamatsu, 619 PMTs are 10-stage 20 cm model
168 R5912, complete with waterproof base assemblies built by Hamamatsu to our
169 specifications. These PMTs are rated to withstand a pressure of up to seven
170 atmospheres, over three times the pressure at the bottom of a pool. The applied
171 positive high voltage and signal are carried with a single 52-m-long Belden
172 YR-29304 50 Ω coaxial cable terminated with a Huber+Suhner 11 SHV-50-4-1
173 connector. The outer jacket of the coaxial cable is high density polyethylene,
174 compatible with ultra-pure water.

175 Recycled from the MACRO experiment [9], 341 PMTs are 8" EMI 14-stage
176 models 9350KA and D642KB. These were assembled with custom bases and wa-
177 terproofed. A 52-m-long JUDD C07947 50 Ω coaxial cable with a polyethylene
178 outer jacket handles the supplied high voltage and signal. The EMI PMT assem-
179 blies were all tested in a pressure vessel filled with water to about 85 kPa (gauge).

180 Prior to installation, the dark rate, rise time, linearity, pre- and after-pulsing
181 probabilities, the peak-to-valley ratio of the digitized single photoelectron wave-
182 form, the gain as a function of applied voltage, and the relative detection effi-
183 ciency of each PMT assembly were measured and archived. At a gain of 2×10^7 ,
184 the PMTs demonstrate a single photoelectron (pe) peak-to-valley ratio of 2.5 or
185 better. A small percentage of the assemblies tested was rejected, such as those
186 with dark rates exceeding 10 kHz at a threshold of 0.25 pe. The characteriza-
187 tion of each PMT determined its HV setting for a nominal data-taking gain of
188 1.0×10^7 , about 20 ADC counts per photoelectron.

189 The PMTs were each pre-assembled with a magnetic shield [10], a bracket,
190 and "Tee" support (Fig. 3). The brackets and "Tees" are type-304 stain-
191 less steel. Small pieces of Viton[®] prevent direct contact between the brackets
192 and PMTs. The PMT assemblies were carefully boxed and labeled with pre-
193 determined installation positions.

Figure 3: Photograph of a Muon PMT assembly, including PMT, base, cable, magnetic shield, bracket, and “Tee”.

2.3. Resistive Plate Chambers

Resistive plate chambers (RPCs) are gaseous particle detectors that consist of two resistive planar electrodes separated by a gas gap [11]. The Daya Bay RPCs are similar to those used by BESIII [12]. The RPC electrodes are $2\text{ m} \times 1\text{ m}$ Bakelite sheets with Melamine surfaces, but, unlike similar RPCs, linseed oil is not applied to the inner surface [13]. The outside of the RPC electrodes is coated with graphite for uniform HV distribution. The gas gap between the two electrodes is 2.0 mm. Daya Bay operates the RPCs in streamer mode, which provides relatively large signals and thereby simplifies the readout electronics. Figure 4 is a schematic of a bare RPC, the functional element of the Daya Bay RPC modules.

RPC modules, $2.17\text{ m} \times 2.20\text{ m} \times 8\text{ cm}$, are constructed from four pairs of side-by-side bare RPCs arranged in layers (Fig. 5), each separated by insulating materials, support panels, ground planes, and copper-clad FR-4 readout planes associated with each pair of side-by-side bare RPCs, inside an aluminum box. The readout planes each have eight $26\text{ cm} \times 2.10\text{ m}$ readout strips oriented like $X\ Y\ Y\ X$. The strips have a zigzag design (Fig. 6), equivalent to strips 6.25 cm wide and 8.4 m long.

Figure 4: The basic structure of a bare RPC. The button spacers maintain a uniform gap, but create small dead areas. The PET layers are a 100 μm polyethylene terephthalate film covering the graphite.

Figure 5: A schematic of the RPC module structure. Each module has four pairs of side-by-side bare RPCs. The “Sunshine” plates are 1.0 cm twin-wall polycarbonate.

Figure 6: Top: The RPC zigzag (or folded) readout pattern, showing four of eight readout strips. Bottom: A single readout strip, vertically expanded to improve visualization of the folds, and showing the readout contacts on the left. The separation between readout strips is 0.25 cm. The folds in a single readout strip are 6.25 cm wide and separated by 0.25 cm.

Each hall has an RPC gas system which mixes argon, freon (R134a), isobutane, and SF_6 in the ratio 65.5:30.0:4.00:0.500 [14]. Each gas system comprises a mixing panel, a main gas distribution panel, a fire/gas safety monitoring system, an MKS Instruments 247D mass flow control system, a Varian GC430 gas chromatograph, and gas supplies in a dedicated utility room. The gas from the main mixing panel is distributed by two independent gas channels to the upper and lower halves of each module, with groups of four bare RPCs connected in series. If one gas channel fails, the other will continue to supply one X and one Y readout. The exhaust of each gas channel is fed into mineral-oil bubblers in racks mounted on the RPC support frame, where the bubbles are electronically counted and recorded. The nominal gas flow rate is about 1 volume per day. The gas mixture is analyzed every two hours by the chromatograph, ensuring the correct gas mixture. The high ambient humidity at Daya Bay, greater than 65%, is absorbed through the RPCs, thereby making the gas mixture sufficiently

226 humid without adding water vapor, which the gas system is capable of doing.

227 The RPC HV system consists of a CAEN 1527LC mainframe in each hall's
228 dedicated electronics room, populated with equal numbers of positive (+6 kV
229 A1732P) and negative (-4 kV A1733N) 12-channel HV cards, with fanout boxes
230 and HV interface boxes in the experimental hall. The systems in EH1 and EH2
231 each use four CAEN HV cards, while there are six in EH3. Each HV channel
232 is divided into 9 channels by a fanout box and distributed to RPCs via RG59
233 cables through an HV interface box mounted on each RPC module. Each RPC
234 layer of a module is connected to one positive and one negative HV channel. If
235 one of the high voltage channels in a module fails, three of the four layers will
236 continue to function.

237 Between January 2008 and July 2009, Gaonengkedi Ltd. Co. (Beijing) pro-
238 duced 756 $2.1\text{ m} \times 1.1\text{ m}$ and 756 $2.1\text{ m} \times 1.0\text{ m}$ bare RPCs for the main
239 RPC arrays in the three experimental halls, a total area of about 3300 m².
240 An additional 24 of each size of bare RPCs were produced for six special mod-
241 ules used to form small RPC telescopes. Concurrent with the production, the
242 bare RPCs were tested using cosmic muons at IHEP, where the average effi-
243 ciency was 96.1%, the noise rate was 0.15 Hz/cm², and the dark current was 2.5
244 $\mu\text{A}/\text{m}^2$ [15]. The characteristics of these RPCs are in agreement with previous
245 experience [16].

246 The bare RPCs that passed all tests (about 12% were rejected) were then
247 assembled into RPC modules and performance-tested at IHEP [17]. The inter-
248 section area of two orthogonal X and Y readout strips defines a $26\text{ cm} \times 26\text{ cm}$
249 patch. The average efficiency of each patch is about 99.8% with a coincidence
250 between any two of the four layers (2/4). The average patch efficiency is about
251 98.0% with a coincidence between any three of the four layers (3/4). Consider-
252 ing the dead areas created by the button spacers (Fig. 4) and bare RPC frames
253 running through the center of each layer (Fig. 5), this agrees well with the simu-
254 lated module 3/4 efficiency based on the measured average bare RPC efficiency
255 of 96.1%. The accepted modules were transported in crates to Daya Bay by
256 truck in several trips during the dry months of 2010 and 2011. Prior to ship-

Figure 7: Sketch of the small (near halls) and large (far hall) pools, all 10 m deep. The wall modules supporting the PMTs are 1 m wide (Fig. 8). The floor framework under the ADs is not shown. The OWS consists of the volume contained within the wall modules and includes the bottom 1 m just above the pool floor. The IWS includes everything else, and extends to the surface of the pool. An optical barrier (not shown) covering the wall modules and floor framework isolates the IWS and OWS from each other.

ping, a determination was made that the effects of vibrations during transport would be negligible.

2.4. Construction and Installation

The pools are octagonal, as shown in Fig. 7, and constructed of poured concrete reinforced with grounded rebar. Each pool has a small sump pit about 1 m² by 1 m deep near one corner, which is used to house a turbine pump for draining. The pool walls extend about 20 cm above the experimental hall floor, forming a concrete curb about 20 cm wide around the pool. The two corner walls nearest the utility rooms in each hall have several 10 and 15 cm penetrations consisting of PVC pipes embedded in the concrete and above the water level, through which pass all of the cables, plumbing, and lines from water level and temperature sensors.

Following a survey of the pool, pairs of anchor holes were drilled into the concrete pool walls at marked locations on a roughly 2 m × 2 m grid, into which steel anchors were epoxied. Each such pair of anchors supports a type-304 stainless steel anchor pad. The anchor pads on each of the eight walls

273 were adjusted with leveling bolts to be co-planar with each other, then grouted
 274 in place. The entire concrete surface of the pool (walls and floor) was then
 275 pressure-washed to remove the laitance which loosely covers newly poured con-
 276 crete. When the concrete was sufficiently dry (less than 4% moisture), three
 277 coats of PermaFlex urethane-based paint were applied. As with all materials
 278 used in the pools in Daya Bay, the PermaFlex was extensively tested for com-
 279 patibility with ultrapure water. Besides being a durable, waterproof coating for
 280 the concrete, it is also an effective barrier against radon penetration. To ensure
 281 adequate and uniform application, each successive coat was a different color.
 282 The color of the top coat plays no role in the optical properties of the pools be-
 283 cause all surfaces are covered with Tyvek. In addition to being compatible with
 284 ultrapure water and nearly opaque, Tyvek is highly reflective [18–20], which
 285 increases the pool light collection efficiency albeit at some cost to signal timing.
 286 Daya Bay uses a highly reflective multi-layer film formed from two pieces of
 287 1082D Tyvek bonded with a layer of polyethylene, for which the reflectivity in
 288 air is more than 96% for wavelengths from about 300 to 800 nm. The reflectivity
 289 is 99% in water [8]. The reflectance is diffuse with a small specular component.

290 After the PermaFlex had cured, Tyvek was draped down over the pool walls
 291 in 2 m wide strips and extended out over the pool floor. Each strip had an extra
 292 12 m at the top of the pool which was folded, covered, and stored on the hall
 293 floor for use in a later installation step. The seams between the strips were all
 294 heat-welded. Pre-assembled wall modules (Fig. 8) were then lowered into place
 295 and fastened to the anchor pads on the pool walls. Each section of the wall
 296 framework comprises three stacked, pre-assembled modules made from type-
 297 304 stainless steel Unistrut¹. All of the materials in the modules, including the
 298 fittings, PMT brackets and “Tees”, and other hardware, are type-304 stainless
 299 steel, and were treated with acid in a process known as “pickling”, which is
 300 necessary to restore stainless-steel surfaces to their full, corrosion-resistant state
 301 following any kind of heating, bending, or machining (any of these actions render

¹Reg. trademark. See, e.g., <http://www.unistrut.com>.

302 stainless steel susceptible to corrosion, especially in ultrapure water).

303 PMT assemblies were then installed on the wall modules in top-down order
304 to minimize risk to installed PMTs from the possibility of damage from falling
305 objects during installation. Because some of the EMI PMTs imploded during
306 pressure testing, indicating that they were less able to withstand pressure than
307 the Hamamatsu PMTs, they were deployed only in the top 2 m of the pool.

308 Once the OWS PMTs were all installed on the wall modules, the Tyvek
309 strips' extra 12 m which had been stored at the top, outside the pool, was fixed
310 to the outer edge of the wall modules and draped down over the inner edge
311 of the wall modules, extending down to one meter above the pool floor ². As
312 before, the seams between the strips were heat-welded. This optically isolates
313 the IWS and OWS at the walls. Cable trays were then mounted on top of the
314 framework, over the Tyvek. Small perforations were made in the Tyvek for
315 fastening the cable tray and IWS PMTs to the Unistrut.

316 The IWS PMTs were then installed on the wall modules. After a pause
317 during which the AD stands were installed, Unistrut was assembled in-place to
318 form the floor framework. Like the wall modules, the floor frames were also
319 leveled with adjustable feet. Following the installation of the OWS floor PMTs,
320 the floor framework was covered with Tyvek, completing the optical isolation
321 of the IWS and OWS, then the IWS floor PMTs were installed. At this point,
322 the ADs were installed on their stands, and the penetrations in the curb were
323 sealed with a waterproof, opaque sealant.

324 After a brief commissioning dry run, the pools were filled with water and cov-
325 ered with a 0.5 mm-thick gas- and light-tight black rubberized cloth supported
326 on stainless steel cables. With the cover and penetration sealing in place, the
327 pools are light-tight and sufficiently gas-tight so that a positive-pressure cover
328 gas of dry nitrogen prevents exposure of the water to air. The flow rate is about
329 80 L/min for the small halls, and 100 L/min for the large.

²Recall that the OWS surrounds the IWS on the sides and bottom, and is everywhere 1 m wide.

Figure 8: Typical wall module. Shown is the bottom module for one of the short walls in the small pools (top and bottom of Fig. 7, left). The “outer edge” (the back, facing away and to the left) is fastened to the wall anchor pads. The bottom modules are all 4 m high and are leveled with adjustable feet which rest on the pool floor. The middle and top modules are all 3 m high, and rest on, and are fastened to, the modules below them. Each PMT (“Tee”) assembly is supported by a pair of L-shaped pieces (not clearly visible) mounted on the Unistrut. The three PMTs on the “inner edge” (the front, facing forward and to the right), just above middle-height, are in the IWS. The other PMTs are in the OWS. The two OWS PMTs mounted on the vertical center support, facing away and to the left, face outward (i.e., away from the ADs), while the other OWS PMTs face inward (see Table 1).

330 In parallel with the installation activities described above, HV interfaces and
 331 Front End Cards (FECs) were installed on the RPC modules on site, which were
 332 then tested for gas tightness and HV integrity before installation. The RPCs
 333 were required to hold 20 cm of water overpressure with a drop rate of less than
 334 2% per day. 8 kV was applied to the RPC modules while they were flushed
 335 with pure argon to check the HV connections and basic performance. Readout
 336 strip and ground connections were also checked. The RPC modules were then
 337 transported to the experimental halls in the same containers in which they were
 338 shipped from Beijing.

339 The RPC modules were laid on a steel support structure in a staggered pat-
 340 tern such that there is 10 cm overlap between neighboring modules to minimize
 341 dead regions (Fig. 9). The RPC support structure is installed on rails, so that
 342 the RPCs can be rolled away to allow access to the pool. There are 6×9
 343 modules in EH1 and EH2, and 9×9 modules in EH3.

344 Two RPC modules were specially installed in each experimental hall to form
 345 the RPC telescopes. These modules are about 2 m above the RPC array, at
 346 the middle on opposing sides of the pool, and partially overlap the RPC array.
 347 Muons that pass through both the telescope and the main RPC array can be
 348 tracked with good angular resolution, as described in § 4.4.

349 *2.5. Readout and Triggering*

350 All hardware related to the powering or readout of detector signals is con-
 351 nected to a Signal Ground that includes the cable trays, wall modules, electrodes
 352 in the rock, a copper grid in the concrete floor outside the pool, and the rebar
 353 of the pool. A separate Safety Ground is brought into the halls with the AC
 354 power, connected to various peripheral systems such as the Detector Controls
 355 System [21] and networking.

356 The Muon System PMTs' signals are fed into ADCs and TDCs. These, and
 357 their readout, are the same as those of the AD PMTs [2, 22, 23]. An IWS or
 358 OWS PMT readout (the two are independent) is initiated by one or more of the
 359 following triggers:

Figure 9: The RPC modules are installed on a support structure in two parallel, partially overlapping layers. Modules are mounted on pairs of the brown supports (higher layer) or on pairs of the green supports (lower layer). Modules in a row alternate between the higher and lower supports, providing overlap in the row-direction. The supports are canted at 3° , providing overlap in the column-direction.

- 360 • Multiplicity Trigger: The PMT multiplicity (the number of PMTs each
361 with charge above a preset threshold) meets or exceeds a preset minimum.
362 Only PMTs above 0.25 pe are read out.
- 363 • Energy Sum Trigger: The total PMT charge exceeds a preset total-charge
364 threshold. Only PMTs above 0.25 pe are read out.
- 365 • Periodic Trigger: Unbiased at 10 Hz. All PMTs are read out.

366 The 32 signal strips in each RPC module are read out and discriminated by
367 one FEC. Up to 15 FECs are read out by one Read Out Transceiver located on
368 the RPC support frame [24]. RPC module triggers are collected and communi-
369 cated to the data acquisition system by an RPC Trigger Module and Read Out
370 Module in the electronics room [25]. An RPC readout is initiated by one of the
371 following triggers:

- 372 • 2/4 Trigger: Any two of the four layers in a module sees a signal above
373 threshold. Only the triggered modules are read out.

- 374 • 3/4 Trigger: Any three of the four layers in a module sees a signal above
375 threshold. Only the triggered modules are read out.
- 376 • Periodic Trigger: Unbiased at 10 Hz. All modules are read out.

377 The Muon System performs its function as a veto strictly in the offline
378 environment. The presence or absence of an IWS, OWS, or RPC trigger does
379 not affect the readout of the AD PMTs. AD readouts are matched with IWS,
380 OWS or RPC readouts with GPS-derived time stamps, accurate to 25 ns. For
381 the IBD event selection, an event is tagged as a muon if either the calibrated
382 total energy in an AD is greater than 20 MeV or if the PMT multiplicity in
383 the IWS or OWS is greater than 12 (considerably higher than the multiplicity
384 trigger requires). The RPCs are not used to tag muons in the oscillation analysis,
385 though they are used in cosmogenic background studies.

386 2.6. Monitoring and Control

387 The Daya Bay Detector Controls System [21] provides the means of remotely
388 monitoring and controlling the detectors' operating parameters for each hall.
389 The water system monitors include water temperature, oxygen content, water
390 level and resistivity. The HV of each water pool PMT is remotely controlled
391 and monitored, and the currents monitored.

392 The RPC gas system monitors include the flow rates of the gas mixture and
393 each of its components, gas tank pressures and weights, gas feed and return
394 humidity, and several status conditions, such as the state of the hazardous gas
395 monitor (which would detect an isobutane leak in the gas room) and interlock
396 status. If the flow rate of any gas component is not within its specified range, the
397 gas system will shut down automatically and send an alarm signal to monitoring
398 personnel. The gas system can also be shut down remotely.

399 The HV of each RPC channel is remotely controlled and monitored, and the
400 dark currents are monitored. The HV and gas systems are interlocked through
401 the remote monitoring program so that, in the case of an alarm signal from the
402 gas system, the HV monitoring program will warn monitoring personnel and

allow them 30 minutes to resolve the issue before automatically turning off the
RPC HV.

The Daya Bay Performance Quality Monitoring system [26] provides the
means of monitoring the performance of the detectors, continuously displaying
the detector trigger rates, individual TDCs and ADCs, and detector channel-
maps, to name a few.

2.7. Commissioning

After the PMTs were all installed in the EH1 pool, and before installing
the ADs and filling with water, a dry run was conducted to perform a full
test of everything from HV, PMT, readout electronics, and the data acquisition
system. A cover was placed over the pool, and HV gradually applied to the
water pool PMTs while checking for light leaks. As expected because of their
recent exposure to bright light, the PMT dark rates were initially elevated.
After a few days the PMTs quieted down somewhat, but their rates were still
substantially higher than expected. One contribution to the elevated rates was
unanticipated fluorescence in the insulating material (polyethylene) on the AD
stands, which scintillates when struck by α particles from radon decay. Once
this problem was identified, the AD stands in EH1 and EH2 were covered with
opaque material, which reduced the PMT rates by about 35%, while a different
insulating material was used in EH3, where the AD stands had not yet been
installed. With this covering in place, the PMT rates (threshold 0.25 pe) were
typically 4 to 5 kHz in the OWS, and 6 to 8 kHz in the IWS. This is to be
compared to what had been measured in the controlled environment of the lab,
where the typical rates were about 1 kHz. This is almost certainly due to α
particles from radon decay, which ionize and excite atmospheric nitrogen [27],
producing light in the PMT-sensitive range of 300-500 nm [28, 29]. Given that
the volume of air in the IWS is so much larger than that in the OWS, it is not
surprising that the IWS rates were substantially higher than the OWS rates in
the dry pool. At the end of the dry run HV was turned off, the cover removed,
and the ADs installed.

Table 2: IWS and OWS trigger thresholds, as of October 22, 2012. For the multiplicity trigger, the single PMT charge threshold is 1.2 mV, which corresponds to 0.25 photoelectrons (pe).

	Pool	Multiplicity Threshold ($\geq$)	Energy Sum Threshold
EH1	IWS	6	8.9 mV (1.8 pe)
	OWS	7	10.0 mV (2.0 pe)
EH2	IWS	6	8.9 mV (1.8 pe)
	OWS	7	10.0 mV (2.0 pe)
EH3	IWS	6	12.2 mV (2.4 pe)
	OWS	8	14.4 mV (2.9 pe)

433 Once each pool was filled with water and covered, the water pool PMTs' HVs
 434 were gradually raised to their full nominal settings while testing for light leaks.
 435 For reasons not entirely understood, a PMT's dark rate generally increases
 436 when it is immersed in water, even in ultrapure water. Although the PMTs
 437 were required to have dark rates less than 10 kHz in the laboratory, some dark
 438 rates remained at 15 kHz after the pools were filled and even after a two-week
 439 period of darkness. The typical rates in EH1 were about 9 kHz for the IWS and
 440 about 14 kHz for the OWS. This difference is expected since the OWS PMTs
 441 are closer to the granite of the pool walls which emit quite high rates of gamma
 442 radiation. The water in the OWS shields the IWS from most of these gammas.
 443 This effect is negligible when the pool is dry, because it operates by generating
 444 Cherenkov light in the water. Based on initial data taken over the first month,
 445 the IWS and OWS thresholds for the multiplicity trigger and charge thresholds
 446 for the energy sum trigger were set as shown in Table 2.

447 Because the underground temperature and humidity were considerably higher
 448 than at IHEP, the RPC dark current at Daya Bay was initially too high at the
 449 HV value of 7.6 kV used in the tests at IHEP. To reduce the ambient humidity
 450 around the RPCs, and thus the dark current, each hall was retrofitted with a
 451 dry air system that blows dry air into the RPC modules. This immediately

reduced the dark current by a factor of two. After steady long-term operation with the new dry air system, the additional reductions in singles rates and dark current eventually allowed the RPCs to be operated at their nominal HV value of 7.6 kV. Based on threshold scans in each hall, the signal thresholds were all set to 35 mV. The threshold was chosen to balance efficiency and noise. The threshold was selected to be higher than the IHEP test setting of 30 mV to reduce the impact of accidentals and other noise. It was determined that the 2/4 trigger produced an excessive volume of RPC data, so the RPCs are read out with only the 3/4 trigger and periodic trigger during Physics data taking, with a loss in efficiency on the order of 1%.

3. Muon and detector simulation

The muon flux at sea-level is reasonably well-described by Gaisser’s formula [30, 31], originally introduced in 1990. However, for our purposes it is necessary to modify this formula [32] to better describe the low energy spectrum, to account for the earth’s curvature, and to better describe large-zenith muons [33–36]. High and low precision topographic maps of the region of the Daya Bay Nuclear Power Plant were merged to obtain a realistic, digitized mountain profile (Fig. 10).

A sample of 10^6 sea-level muons was generated for each hall with the modified Gaisser formula. The path length through rock of each muon was calculated using an interpolation based on the digitized mountain profile. The muons were transported with the MUSIC code [38, 39] through the rock to get the underground muon sample. Table 3 shows the simulated muon flux and average energy at each hall. Figures 11 and 12 show the simulated muon angular and energy distributions at each hall. The simulation error from MUSIC is about 1%. Considering the uncertainties in mountain profile mapping, rock composition, and density profiling, the total error in the simulated muon flux is estimated to be about 10%.

The water shield simulation included detailed Cherenkov photon emission

Figure 10: 3D image of the Daya Bay area generated by ROOT [37] from the digitized mountain profile. The tunnel entrance is at the base of the mountain at the left side of the figure.

Table 3: Underground muon simulation results. The error in the simulated flux is about 10%. All values have been transformed into a detector-independent spherical geometry.

Hall Overburden			Muon flux Hz/m^2	Average Energy GeV
m	mwe			
EH1	93	250	1.27	57
EH2	100	265	0.95	58
EH3	324	860	0.056	137

Figure 11: Simulated muon trajectories. By definition, zenith is the angle from vertical and azimuth is the horizontal compass angle from true North.

Figure 12: Simulated muon energy spectra. Each curve includes 10^6 simulated muons.

481 and propagation through the water with conservative assumptions of water at-
 482 tenuation length and PMT quantum efficiency. The propagation of Cherenkov
 483 light was modeled with the full detector geometry, including reflection from the
 484 ADs and IWS/OWS optical barriers. The Tyvek reflectivity in water was de-
 485 scribed by a full optical model in Geant4 with several parameters which were
 486 tuned based on studies in the IHEP prototype tank. The simulation also in-
 487 cluded the expected behavior of the electronics. Comparisons with real data
 488 revealed that the simulation was accurate, except that some of the assumptions
 489 were too conservative – the water Cherenkov detector performs better than the
 490 simulations predicted. Various scenarios of PMT failures were also modeled,
 491 demonstrating that the pools are populated with more PMTs than needed to
 492 reach design-performance. For example, a simulated failure of 20% of the PMTs,
 493 randomly distributed, was compensated for by reducing the multiplicity thresh-
 494 old, thereby achieving the same muon tagging efficiency as with no failures.

495 The RPC system was simulated with the full detector geometry, including
 496 the layout of the modules and the layout within a module: four layers of RPCs,
 497 readout strips, and buffer materials, the latter corresponding to the labeled
 498 planes in Fig. 5. The RPC array and RPC telescopes were positioned according
 499 to on-site surveys. Individual RPCs incorporated both Bakelite and RPC gas
 500 properties. The gas gaps were sensitive to any particle that deposited energy
 501 and were assigned individual efficiencies determined by on-site calibration [40].
 502 All the electronic components mentioned in § 2.5 were also simulated. Random
 503 noise events were mixed with muon events based on a global bare RPC noise rate.
 504 In addition, dead areas were implemented with the 1 cm-wide RPC frames and a
 505 simplified geometry for the button spacers. Given that the module supports have
 506 a sloping angle of about 3° (Fig. 9), the azimuthal orientation of the supports
 507 was chosen to minimize the effective dead area in the direction of maximum
 508 muon flux. According to simulations, this choice could affect acceptance by
 509 0.3-0.6%, depending on the hall. A comparison between simulation and data of
 510 the angular distribution of reconstructed muons is presented in § 4.4.

Figure 13: Water Cherenkov PMT gains (single photoelectron charge) vs. time. The jumps in the EH1 gains in early May were caused by temperature changes in the electronics crates. There is about three times more activity, and therefore more frequent calibration, in a given OWS than in the corresponding IWS.

4. Performance

From December 2011 through July 2012, the Daya Bay experiment collected data with six ADs installed: two ADs in EH1 (AD1 and AD2), one in EH2 (AD3), and three in EH3 (AD4, AD5, and AD6). By September 2012 the two final ADs were installed. This section discusses data taken in the first period, when only six of the eight ADs were deployed.

4.1. PMT gains and detector rates

Data from the periodic trigger is used to perform continuous PMT gain calibration from dark noise. Figure 13 shows the water Cherenkov PMTs' average gain versus time for the three halls. The average PMT gains are relatively stable with a slight upward trend over time. PMT noise affects the multiplicity trigger and, therefore, the vetoing efficiency. Figure 14 shows the multiplicity trigger and average PMT dark noise rates versus time. These do not change much over time except for a few episodes caused by noisy electronics.

Data from the RPC periodic trigger is used to determine RPC layer noise rates for each run. Figure 15 shows the noise rate of the RPC layers, as a

Figure 14: **Top:** Multiplicity trigger rate vs time. **Bottom:** Water Cherenkov PMT dark noise rate vs time, from periodic triggers. The gaps differ somewhat in the two plots because they are made from different trigger types.

Figure 15: Noise rate for the RPC layers in each hall. On March 16, the HV was increased from 7.4 to 7.6 kV (the nominal operating voltage), which yielded a few percent increase in muon efficiency but also increased the noise. The thresholds were set to 35 mV throughout this period. Larger error bars are due to fewer samplings (shorter runs). The two-week gap in EH1 in April is due to a failed mass flow controller. Fine structures are due to variations in hall temperature and humidity.

function of time. The average rates decrease over time, as expected.

4.2. Water quality

A readily measured indicator of water quality is the resistivity: The higher the resistivity, the purer the water³, although this is a poor proxy for the attenuation length (e.g., adding salt to water does not change its attenuation length). The water resistivity is continually monitored at Daya Bay (Fig. 16A). The resistivity in EH2 and EH3 steadily increases (improves) over several weeks of operation. In contrast, the resistivity in EH1 shows no significant improvement with time, most likely due to an unidentified source of contamination. This has not negatively affected the performance of the veto, however, as demonstrated below.

A better proxy for the water attenuation length is the mean multiplicity per muon⁴, plotted over a period of time in Fig. 16B. The OWS mean multiplic-

³For ultrapure water, the maximum is 18.2 MΩ-cm at 25 C.

⁴Here, “muon” indicates that the observed PMT multiplicity exceeded 12. It does not

Figure 16: Three water-clarity proxies. **A:** Resistivity of the pool water in each hall vs. time. This measurement is made where water from the pool re-enters the polishing loop. The water delivered to the pool is typically 14 to 16 M Ω -cm. The jump in EH1 on May 4 was due to sensor maintenance. **B:** Mean PMT multiplicity per muon vs. time. **C:** The decay time τ from Eq. (1), fit to data from short periods of time in all halls, as a function of time. Longer decay times correspond to clearer water (see text).

ities of EH1 and EH2 are very similar as might be expected, but that of the IWS for EH2 is much higher than for EH1. This is because during the period shown, EH2 had only one AD in the pool, whereas EH1 had two. That the IWS mean multiplicities of EH2 and EH3 are nearly the same is essentially accidental, considering the larger IWS, lower muon flux, and higher trigger thresholds (Table 2) in EH3. The lower mean multiplicity in the EH3 OWS is due to PMT and electronics noise, which produce a larger fraction of low-multiplicity triggers in the EH3 OWS than elsewhere.

Another proxy for the water attenuation length is the decay time of light (including reflected light) in a pool from the passage of a muon. This is complicated by reflection losses from the Tyvek and other materials, some of which have a reflectivity of less than 50% (such as the ADs), but changes in the water attenuation length would be apparent when the decay time is followed over time, all else remaining fixed. To characterize this decay time in the pools, all PMTs' threshold-crossing times are accumulated in one histogram for the IWS, and another for the OWS (Fig. 17). These two distributions are then fit with the heuristic form

$$\begin{aligned}
 f(t) &= A b(t) \frac{a_0 - a_1(t)}{2\tau} + C_0 \\
 a_0 &= \operatorname{erf}\left(\frac{\sigma^2 + \tau t_0}{\sqrt{2}\tau\sigma}\right) \\
 a_1(t) &= \operatorname{erf}\left(\frac{\sigma^2 - \tau(t - t_0)}{\sqrt{2}\tau\sigma}\right) \\
 b(t) &= \exp\left(\frac{\sigma^2 - 2\tau(t - t_0)}{2\tau^2}\right)
 \end{aligned} \tag{1}$$

where A, C_0, t_0, σ , and τ (the light decay time) are fit parameters and t is the PMT time from the histograms. Figure 17 shows the results of fitting Eq. (1) to some EH1 OWS data, for which $\tau = 42.54 \pm 0.09$ ns. The variation of τ with time for all pools is shown in Fig. 16C. As with the mean multiplicity per

indicate an actual particle identification, though with so many PMTs seeing light at the same time, and being deep underground, it is almost always indeed a muon.

Figure 17: A typical fit to Eq. (1) to data from a short period of time in EH1 OWS.

muon, Fig. 16B, the variation of the decay time τ with time is very small after the water systems had been running for about a month. The three plots in Fig. 16 indicate a slight improvement in water quality over the period covered.

Figure 18 shows distributions of the PMT multiplicity per muon. The IWS multiplicity differs from hall to hall because of the different configurations (numbers of deployed ADs). The OWS configurations in EH1 and EH2 are the same, however, so their respective distributions are also nearly the same. The EH2 OWS average is slightly higher than that of EH1, which can also be seen in Fig. 16B, indicating that the EH2 water is clearer than that of EH1.

The water is essentially free of all radioactive sources, except for radon. Radon is pervasive in an underground, granite environment, and will enter the water through any contact with air, and through the pool walls and from all the steel in the pool as a product of the uranium or thorium decay chain. The former is controlled by avoiding contact with air, which is one function of the pool cover gas (it also prevents O_2 and CO_2 from entering the water). The latter source is controlled by the PermaFlex, but this path of entry cannot be completely eliminated. Along with other gasses, the water polishing stations remove radon, but it is constantly replenished. Table 4 shows the radon activity

Figure 18: Distributions of PMT Multiplicity-per-muon. The peak below 20 PMTs, most prominent for EH3 OWS, is mainly due to PMT and electronics noise.

Table 4: Radon activity in the water before and after polishing.

Hall	Before polishing Bq/m ³	After polishing Bq/m ³
EH1	34.7 ± 4.2	30.2 ± 3.6
EH2	86.4 ± 9.6	49.6 ± 5.5
EH3	48.4 ± 6.3	43.3 ± 4.9

579 measured in the water polishing stations. These levels are within the Daya Bay
580 design requirements.

581 4.3. Muon-detection efficiency

582 Muons going through an AD (which detects them with essentially 100%
583 efficiency) can be used to measure IWS and OWS efficiencies. Figure 19 gives
584 the rate of muons in the ADs (events with more than 20 MeV in an AD). Each
585 AD has a muon rate of ~ 20 Hz in EH1, ~ 15 Hz in EH2, and ~ 1 Hz in EH3,
586 which correspond to the overburdens in the respective halls. Figure 20 shows
587 the IWS efficiency, for an IWS trigger of >12 coincident PMTs, measured by
588 AD-tagged muons versus time. The mean IWS efficiency for all three halls is

Figure 19: Rate of muons (depositing more than 20 MeV in an AD) in the ADs versus time. Half the symbols in the plot are mostly obscured because the ADs' rates from a given hall are essentially the same.

589 well-described by a single value

$$\xi_{\text{IWS}} = 99.98 \pm 0.01\% . \quad (2)$$

590 The small apparent inefficiency is due to events identified as muons in an AD,
591 but which are actually neutrons created by muons in the rock. Neutrons can
592 propagate undetected through the water into an AD, and deposit sufficient en-
593 ergy to be tagged as a muon. While simulations indicate that the IWS efficiency
594 for AD-tagged muons should be 100%, they also show a very small fraction of
595 muons showering in the rock, where a neutron deposits energy in an AD but
596 without a charged particle passing through the water. This simulated fraction
597 is consistent with the observed IWS inefficiency.

598 Figure 21 shows the OWS efficiency measured by AD-tagged muons versus
599 time. This is expected to be lower than the true OWS efficiency because of
600 muons that deposit energy in the ADs but stop there or in the IWS either
601 without traversing the OWS at all, or by traversing only a short path in the
602 OWS. (Recall that the OWS does not cover the top of the IWS.) This happens
603 less often in EH3 because of the higher mean energy of the muons in EH3, as
604 can be seen by its higher AD-measured efficiency. Muons entering through the
605 side will be seen in the OWS and do not contribute to this inefficiency. Table 5

Figure 20: IWS efficiency for AD-tagged muons vs time.

Figure 21: OWS efficiency for AD-tagged muons vs time.

606 shows the measured and simulated OWS efficiencies.

607 Table 6 shows the underground muon flux at each hall, as determined by each
 608 detector subsystem. The selection criteria in the three systems are deposited
 609 energy >20 MeV for the ADs, more than 20 PMTs for the IWS and OWS above
 610 0.25 pe, and four out of four triggered planes plus a strip cut for the RPCs.⁵
 611 Corrections are made for the efficiency of each detector. All values are consistent
 612 with the simulation results in Table 3.

⁵RPC efficiency and muon flux are determined in [40]. The strip cut requires that each triggered layer has only one or two adjacent triggered strips.

Table 5: OWS measured and simulated (MC) efficiencies ξ_{OWS} .

	EH1	EH2	EH3
Data	$97.2 \pm 0.2\%$	$97.4 \pm 0.2\%$	$98.7 \pm 0.2\%$
MC	$97.4 \pm 0.1\%$	$96.6 \pm 0.2\%$	$98.0 \pm 0.2\%$
Difference	$-0.2 \pm 0.2\%$	$0.8 \pm 0.3\%$	$0.7 \pm 0.3\%$

Table 6: Measured underground muon flux (Hz/m^2). The simulated flux from Table 3 is included for comparison. All values have been transformed into a detector-independent spherical geometry. The errors are dominated by the systematic uncertainty of the transformation, which is the difference between assuming the simulated vs. measured angular spectrum.

Detector	EH1	EH2	EH3
AD	1.21 ± 0.12	0.87 ± 0.09	0.056 ± 0.006
IWS	1.15 ± 0.12	0.86 ± 0.09	0.055 ± 0.005
OWS	1.12 ± 0.11	0.84 ± 0.08	0.053 ± 0.005
RPC	1.17 ± 0.09	0.87 ± 0.11	0.053 ± 0.006
Average	1.16 ± 0.11	0.86 ± 0.09	0.054 ± 0.006
Simulation	1.27 ± 0.13	0.95 ± 0.10	0.056 ± 0.006

613 4.4. Muon angular distributions

614 Muon trajectories can be reconstructed from the main RPC array and the
615 telescope RPCs, which are described at the end of § 2.4. The position resolution
616 in these devices is about 10 cm which corresponds to roughly 2° in zenith and
617 4° in azimuth. This reconstruction uses the same event selection as the muon
618 flux calculation.

619 The angular coverage of the telescopes is shown in Fig. 22, which compares
620 data with a simulation for EH1. They are consistent within the reported errors
621 in simulation and measurement. The data-excess at large zenith might be due
622 to accidental muon coincidences, which were not simulated. The accidental
623 coincidence rate between the main RPC array and the RPC telescopes increases
624 with zenith as the number N_{geo} of modules geometrically available for accidentals
625 increases until about 75° , where N_{geo} begins to decrease. The bare RPC noise
626 rate is several orders of magnitude too small to make a noticeable contribution
627 to these accidentals (see Fig. 15).

628 4.5. PMT failures

629 Between the time when the EH1 pool was first filled in August of 2011 and
630 the shutdown in the summer of 2012, 13 PMTs had failed in the three halls.
631 These were all EMI PMTs, recycled from the MACRO experiment [9]. Because
632 the EMI PMTs were all deployed in the top two meters of the pool, these failures
633 were all near the top of the pool, but otherwise randomly distributed. Most of
634 these PMTs failed in the first month or two after their respective pool was filled.
635 Failures continued after this initial period, though at a reduced rate. During
636 the summer of 2012, most of the failed PMTs (i.e., those that were accessible)
637 were replaced with Hamamatsu PMTs during maintenance operations which
638 included the installation of the final two ADs in EH2 and EH3. Examination
639 of the failed PMTs revealed that they had mostly suffered very small cracks in
640 the glass, through which the vacuum drew in water. Only one of these PMTs
641 had shattered. Upon refilling in September 2012, nine more PMTs immediately
642 failed, all EMI. As of August 2014, another 14 PMTs failed, with a mean time

Figure 22: RPC-reconstructed muon trajectories in EH1. The MC and data points are normalized by their respective total counts. Corrections are made for the measured efficiencies.

between failures of about 40 days. Of these latest failures, essentially at random intervals of time, three were Hamamatsu PMTs (one in each of the three halls) and the rest were EMI. As with the first 13 failures, these later EMI failures were all near the top of the pool, and randomly distributed. One Hamamatsu failure was on the bottom of the pool, while the other two were about two meters above the bottom. The total fraction of failed PMTs is just below 4%, far below the simulated 20% failures which was shown to have no effect on performance.

5. Conclusion

The muon system performs as required by the design specifications, with a muon detection efficiency not significantly different from 100% for the IWS alone. The small apparent IWS inefficiency of 0.02 ± 0.01 %, as determined from muons identified by the ADs, is consistent with neutron background in the ADs. The somewhat larger apparent inefficiency in the OWS is consistent with muons that stop in the AD or IWS without reaching the OWS, rather than a true inefficiency in the OWS. Indirect studies show that the water attenuation length is about 40 m, but it has not yet been definitively measured. The independent proxies for quantifying water quality discussed in § 4.2 support this level of clarity, and demonstrate that the water-compatibility program mentioned in § 2.1 was successful. PermaFlex has proved itself to be an effective coating for the pool: Had the water made direct contact with the concrete, the water quality could not have been as good as observed. The water treatment systems have also performed well.

Unplanned interventions and modifications made as needs arose improved the experiment, such as the covering or replacement of the fluorescing insulating material on top of the AD stands, and the addition of a dry air system around the RPCs to reduce the dark currents which were higher than expected because of the high ambient humidity of the sub-tropical climate at Daya Bay. Although it occurred in the (late) planning stage, the recognition that the warm climate at Daya Bay required cooling of the water should be considered to be in this

672 same category of interventions, since the original plan specified only that the
673 water would be heated. Measurements of the underground rock temperature
674 revealed that the water would be too warm, rather than too cool, reflecting
675 a northern-climate bias in the early planning stage. The constructed cooling
676 capacity was successful in maintaining its design goal of 24 ± 1 C water.

677 In addition to its main function as background shield and muon veto, the
678 muon system also serves to study background in the IBD signal. There remain
679 contributions to this background from muons that completely miss the pools
680 and the RPCs, or have only very short paths in the pools, while producing fast
681 neutrons in the rock which find their way to an AD and produce a false IBD
682 signature. Small corrections for these contributions, based on simulations, are
683 made in the full neutrino analysis [1]. The results presented in § 4 demonstrate
684 the veracity of these simulations.

685 Given the much higher failure rate of the EMI PMTs, the decision to recycle
686 these PMTs from the MACRO experiment was perhaps somewhat unfortunate.
687 Nevertheless, this has had no impact on the results of the Daya Bay experiment.
688 With a mean time between PMT failures of 40 days, the Daya Bay Experiment
689 will have completed a five year run long before 20% of the water pool PMTs
690 have failed, the level of failure which has been shown by simulations to have no
691 impact on the muon veto efficiency.

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