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<tr>
<th>Title</th>
<th>Observation of electron-antineutrino disappearance at Daya Bay</th>
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<tr>
<td>Author(s)</td>
<td>An, FP; Bai, JZ; Balantekin, AB; Band, HR; Beavis, D; Beriguete, W; Bishai, M; Blyth, S; Boddy, K; Brown, RL; Cai, B; Newsom, C; Ngai, HY; Ngai, WK; Zhang, ZP; Nie, YB; Seilhan, B; Ning, Z; Chang, Y; OchoaRicoux, JP; Zhan, L; Huang, PW; Oh, D; Tsang, RHM; Olshesvki, A; Pagac, A; Patton, S; Pearson, C; Zhang, ZY; Shao, BB; Pec, V; Chen, HS; Huang, X; Lai, WC; Viren, B; Shih, K; Virostek, S; Kettell, SH; Li, XB; Vorobel, V; Wang, CH; Wang, LS; Li, B; Huang, XT; Chen, SJ; Song, JC; Wang, LY; Wang, LZ; Wang, M; Wang, NY; Kramer, M; Wang, RG; Steiner, H; Wang, T; Tang, X; Wang, W; Wang, X; Zhang, C; Wang, X; Li, F; Wang, YF; Chen, SM; Wang, Z; Kwan, KK; Wang, Z; Huber, P; Wang, ZM; Zhao, QW; Webber, DM; Chen, Y; Wei, YD; Wen, LJ; Wenman, DL; Whisnant, K; Li, GS; White, CG; Lee, M; Kwok, MW; Whitehead, L; Chen, XC; Whitten, CA; Zhang, FH; Zhao, YB; Wilhelmi, J; Wise, T; Wong, HC; Wong, HLH; Isvan, Z; Wong, J; Worcester, ET; Liang, J; Li, J; Wu, FF; Zhang, JW; Wu, Q; Xia, DM; Zheng, L; Chen, XH; Jaffe, DE; Xiang, ST; Xiao, Q; Xing, ZZ; Xu, G; Kwok, T; Xu, J; Zhang, QM; Xu, J; Li, QJ; Xu, JL; Jetter, S; Xu, W; Zhong, WL; Xu, Y; Xue, T; Chen, X; Yang, CG; Lai, CY; Zhang, K; Yang, L; Li, WD; Qian, X; Zhou, ZY; Zhang, QX; Zhuang, HL; Piilonen, LE; Torun, Y; Cherwinka, JJ; Zou, JH; Chu, MÇ; Stoler, P; Li, XN; Ye, M; Cummings, JP; Deng, ZY; Ding, YY; Diwan, MV; Pinsky, L; Dong, L; Zhang, SH; Draeger, E; Du, XF; Dwyer, DA; Ji, XL; Edwards, WR; Sun, GX; Ely, SR; Cao, GF; Fang, SD; Chasman, C; Fu, JY; Fu, ZW; Lai, WH; Ge, LQ; Liang, H; Ghazikhanian, V; Gill, RL; Goett, J; Gonchar, M; Sun, JL; Gong, GH; Pun, CSJ; Gong, H; Li, XQ; Gornushkin, YA; Ji, XP; Lau, K; Greenler, LS; Gu, WQ; Guan, MY; Guo, XH; Hackenburg, RW; Hahn, RL; Tull, C; Tam, YH; Hans, S; Jiang, HJ; He, M; He, Q; Lebanowsksi, L; Li, Y; He, WS; Heeger, KM; Heng, YK; Hinrichs, P; Qi, FZ; Ho, TH; Jiang, WQ; Hor, YK; Tanaka, HK; Hsiung, YB; Hu, BZ; Lee, J; Hu, T; Hu, T; Li, ZB; Huang, HX; Qi, M; Jiao, JB; Huang, HZ; Themann, H; Leitner, R; Johnson, RA; Leung, JKC; Yen, M; Zhao, J; Lin, CJ; Leung, KY; Lin, GL; Zhang, YC; Chen, HY; Lin, SK; Lin, SX; Lin, YC; Cao, J; Yeh, YS; Ling, JJ; Kang, L; Link, JM; Littenberg, L; Littlejohn, BR; Liu, BJ; Zhang, YH; Liu, C; Lewis, CA; Liu, DW; Li, SF; Liu, H; Liu, JC; Raper, N; Liu, JL; Carr, R; Liu, S; Liu, X; Liu, YB; Zhang, YX; Lu, C; Yip, K; Lu, HQ; Trentalange, S; Luk, A; Rosero, R; Luk, KB; Luo, T; Luo, XL; Ma, LH; Chan, WT; Ma, QM; Zhou, L; Zhang, ZJ; Ma, XB; Ma, XY; Ma, YQ; Roskovec, B; Tsai, O; Mayes, B; McDonald, KT; McFarlane, MC; McKeown, RD; Young, BL; Meng, Y; Mohapatra, D; Chen, YX; Chang, JF; Morgan, JE; Ruan, XC; Nakajima, Y; Napolitano, J; Tsang, KV; Naumov, D; Yu, ZY; Nemchenok, I</td>
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<td>Physical Review Letters, 2012, v. 108 n. 17, article no. 171803</td>
</tr>
</tbody>
</table>
Observation of Electron-Antineutrino Disappearance at Daya Bay


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where \( \Delta m^2 \) and correspond to the Pontecorvo-Maki-Nakagawa-Sakata matrix, and two measurable \( \Delta m^2 \) values by comparing the observed (ADs), as illustrated in Fig. 1, allows for a relative measurement by the detector (baseline).

For reactor-based experiments, an unambiguous determination of \( \theta_{13} \) can be extracted via the survival probability of the electron-antineutrino \( \bar{\nu}_e \) at short distances from the reactors,

\[
P_{\text{sur}} = 1 - \sin^2 2\theta_{13} \sin^2 (1.267 \Delta m^2 L / E),
\]

where \( \Delta m^2 = \Delta m^2_{21} \pm \Delta m^2_{31} \), \( E \) is the \( \bar{\nu}_e \) energy in MeV and \( L \) is the distance in meters between the \( \bar{\nu}_e \) source and the detector (baseline).

The near-far arrangement of antineutrino detectors (ADs), as illustrated in Fig. 1, allows for a relative measurement by comparing the observed \( \bar{\nu}_e \) rates at various baselines. With functionally identical ADs, the relative rate is independent of correlated uncertainties and uncorrelated reactor uncertainties are minimized.

A detailed description of the Daya Bay experiment can be found in Refs. [7,8]. Here, only the apparatus relevant to this analysis will be highlighted. The six pressurized water reactors are grouped into three pairs with each pair referred to as a nuclear power plant (NPP). The maximum thermal power of each reactor is 2.9 GW. Three underground experimental halls (EHs) are connected with horizontal tunnels. Two ADs are located in EH1 and one in EH2 (the near halls). Three ADs are positioned near the oscillation maximum in the far hall, EH3. The vertical overburden in equivalent meters of water (m.w.e.), the

![FIG. 1 (color online). Layout of the Daya Bay experiment. The dots represent reactors, labeled as D1, D2, L1, L2, L3, and L4. Six ADs, AD1–AD6, are installed in three EHs.](image-url)
simulated muon rate and average muon energy, and average
distance to the reactor pairs are listed in Table I.

As shown in Fig. 2, the ADs in each EH are shielded
with $\geq 2.5$ m of high-purity water against ambient radia-
tion in all directions. Each water pool is segmented into
inner and outer water shields (IWS and OWS) and instru-
mented with photomultiplier tubes (PMTs) to function as
Cherenkov-radiation detectors whose data were used by
offline software to remove spallation neutrons and other
cosmogenic backgrounds. The detection efficiency for
offline software to remove spallation neutrons and other
Cherenkov-radiation detectors whose data were used by

The energy calibration constant, $\sim 163$ pe/MeV for all
ADs and stable throughout the data collection period,
was determined by setting the energy peak of the $^{60}$Co
source deployed at each AD center to 2.506 MeV. Vertex
reconstruction was based on center-of-charge, defined as
the charge-weighted-mean of the coordinates of all PMTs.
The mapping from center-of-charge to vertex was done by
analytic corrections determined using data collected with
$^{60}$Co sources deployed at various points within the AD. A
vertex-dependent correction to energy ($< 10\%$) and a con-
stant factor (0.988) were applied equally to all ADs to
correct for geometrical effects and energy nonlinearity
between the $^{60}$Co and the neutron capture on Gd ($n$Gd),
determined by the $^{60}$Co and Am- C sources at the detector
center. An independent energy calibration that utilized the
peak of the $n$Gd from spallation neutron to set the energy
scale and templates derived from Monte Carlo simulations
(MC) for vertex reconstruction, gave consistent perfor-
ance [7]. The energy resolution was $(7.5/\sqrt{E(\text{MeV})} +
0.9\%)$ for all 6 ADs.

IWS and OWS triggers with NHIT $> 12$ were classified as
“WS muon candidates” or $\mu_{\text{WS}}$. Events in an AD within
$\pm 2 \mu$s of a $\mu_{\text{WS}}$ with energy $> 20$ MeV and $> 2.5$ GeV
were classified as muons ($\mu_{\text{AD}}$) and showering muons
($\mu_{\text{sh}}$), respectively, for vetoing purposes. An instrumen-
tal background due to spontaneous light emission from a
PMT, denoted as a flasher, was rejected efficiently [7].

IBD events were selected with the following criteria:
$0.7 < E_{\nu} < 12.0$ MeV, $6.0 < E_{\bar{\nu}} < 12.0$ MeV, $1 < \Delta t <
200 \mu$s, the prompt-delayed pair was vetoed by preceding

<table>
<thead>
<tr>
<th>Overburden</th>
<th>$R_\mu$ (Hz/m$^3$)</th>
<th>$E_\mu$ (GeV)</th>
<th>D1,2</th>
<th>L1,2</th>
<th>L3,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>250</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
</tr>
<tr>
<td>EH2</td>
<td>265</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
</tr>
<tr>
<td>EH3</td>
<td>860</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
</tr>
</tbody>
</table>

TABLE I. Vertical overburden (m.w.e.), muon rate
$R_\mu$ (Hz/m$^3$), and average muon energy $E_\mu$ (GeV) of the three
EHs, and the distances (m) to the reactor pairs.

FIG. 2 (color online). Schematic diagram of the Daya Bay
detectors.
muons if \( t_d - t_{\mu ws} < 600 \, \mu s \), \( t_d - t_{\mu AD} < 1000 \, \mu s \), or \( t_d - t_{\mu AD} < 1 \, s \), and a multiplicity cut that requires no additional \( >0.7 \, \text{MeV} \) trigger in the time range \( (t_p - 200 \, \mu s, t_d + 200 \, \mu s) \), where \( E_p (E_d) \) is the prompt (delayed) energy and \( \Delta t = t_d - t_p \) is the time difference between the prompt and delayed signals. Statistically consistent performance was achieved by an independent analysis that used different energy reconstruction, muon veto, and multiplicity cuts.

The inefficiency of the muon veto for selecting IBD events \((1 - \epsilon_\mu)\) was calculated by integrating the vetoed time of each muon with temporal overlaps taken into account. Inefficiency due to the multiplicity selection \((1 - \epsilon_m)\) was calculated by considering the probability that a random signal occurred near an IBD in time. The average values of \( \epsilon_\mu \epsilon_m \) are given for each AD in Table II.

We considered the following kinds of background: accidental correlation of two unrelated signals, \( \beta\)-\( n \) decay of \(^{9}\text{Li–}^{8}\text{He}\) produced by muons in the ADs, fast-neutron backgrounds produced by muons outside the ADs, \(^{13}\text{C(n,n)\(}^{16}\text{O}\) interactions, and correlated events due to the retracted Am–C neutron source in the ACUs. The estimated background rates per AD are summarized in Table II.

The accidental background was determined by measuring the rate of both prompt- and delayed-type signals, and then estimating the probability that two signals randomly satisfied the \( \Delta t \) required for IBD selection. Additional estimates using prompt and delayed candidates separated by more than 1 ms or 2 ms provided consistent results. The uncertainty in the measured accidental rate was dominated by the statistical uncertainty in the rate of delayed candidates.

The rate of correlated background from the \( \beta\)-\( n \) cascade of \(^{9}\text{Li–}^{8}\text{He}\) decays was evaluated from the distribution of the time since the last muon using the known decay times for these isotopes [11]. The \(^{9}\text{Li–}^{8}\text{He}\) background rate as a function of the muon energy deposited in the AD was estimated by preparing samples with and without detected neutrons 10 \( \mu s \) to 200 \( \mu s \) after the muon. A 50% systematic uncertainty was assigned to account for the extrapolation to zero deposited muon energy.

An energetic neutron entering an AD can form a fast-neutron background by recoiling off a proton before being captured on Gd. By relaxing the \( E_p < 12 \, \text{MeV} \) criterion in the IBD selection, a flat distribution in \( E_p \) was observed up to 100 MeV. Extrapolation into the IBD energy region gave an estimate for the residual fast-neutron background. A similar flat distribution was found in the muon-tagged fast-neutron sample produced by inverting the muon veto cut. Consistent results were obtained by scaling the muon-tagged fast-neutron rate with muon inefficiency, and by MC.

The \(^{13}\text{C(\alpha,n)\(}^{16}\text{O}\) background was determined using MC after estimating the amount of \(^{238}\text{U}, \, ^{232}\text{Th}, \, ^{227}\text{Ac},\) and \(^{210}\text{Po}\) in the Gd-LS from their cascade decays, or by fitting their \( \alpha\)-particle energy peaks in the data.

A neutron emitted from the 0.5 Hz Am–C neutron source in an ACU could generate a \( \gamma\)-ray via inelastic scattering in the SSV before subsequently being captured on Fe–Cr–Mn–Ni. An IBD was mimicked if both \( \gamma\) rays from the scattering and capture processes entered the scintillating region. This correlated background was estimated using MC. The normalization was constrained by the measured rate of single delayed-type candidates from this source.

Table III is a summary of the absolute efficiencies and the systematic uncertainties. The uncertainties of the absolute efficiencies are correlated among the ADs. No relative efficiency, except \( \epsilon_\mu \epsilon_m \), was corrected. All differences between the functionally identical ADs were taken as uncorrelated uncertainties.

The spill-in enhancement resulted when neutrons from IBD outside the target drift into the target, and was evaluated using MC. The spillout deficit (\( \sim 2\% \)) was included in the absolute Gd capture ratio. The Gd capture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBD candidates</td>
<td>28935</td>
<td>28975</td>
<td>22466</td>
<td>3528</td>
<td>3436</td>
<td>3452</td>
</tr>
<tr>
<td>No-oscillation prediction for IBD</td>
<td>28647</td>
<td>29096</td>
<td>22335</td>
<td>3566.5</td>
<td>3573.0</td>
<td>3535.9</td>
</tr>
<tr>
<td>Data acquisition live time (days)</td>
<td>49.5530</td>
<td>49.4971</td>
<td>7.0389</td>
<td>0.8785</td>
<td>0.8800</td>
<td>0.8952</td>
</tr>
<tr>
<td>( \epsilon_\mu \epsilon_m )</td>
<td>0.8019</td>
<td>0.7989</td>
<td>0.8386</td>
<td>0.9547</td>
<td>0.9543</td>
<td>0.9538</td>
</tr>
<tr>
<td>Accidental signals (per day)</td>
<td>9.82 \pm 0.06</td>
<td>9.88 \pm 0.06</td>
<td>6.76 \pm 0.05</td>
<td>3.29 \pm 0.03</td>
<td>3.33 \pm 0.03</td>
<td>3.12 \pm 0.03</td>
</tr>
<tr>
<td>Fast-neutron (per day)</td>
<td>0.84 \pm 0.28</td>
<td>0.84 \pm 0.28</td>
<td>0.74 \pm 0.44</td>
<td>0.04 \pm 0.04</td>
<td>0.04 \pm 0.04</td>
<td>0.04 \pm 0.04</td>
</tr>
<tr>
<td>(^{9}\text{Li–}^{8}\text{He} ) (per AD per day)</td>
<td>3.1 \pm 1.6</td>
<td>1.8 \pm 1.1</td>
<td>0.16 \pm 0.11</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Am-C correlated (per AD per day)</td>
<td></td>
<td></td>
<td></td>
<td>0.2 \pm 0.2</td>
<td></td>
<td></td>
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<tr>
<td>(^{13}\text{C(\alpha,n)(}^{16}\text{O} ) background (per day)</td>
<td>0.04 \pm 0.02</td>
<td>0.04 \pm 0.02</td>
<td>0.035 \pm 0.02</td>
<td>0.03 \pm 0.02</td>
<td>0.03 \pm 0.02</td>
<td>0.03 \pm 0.02</td>
</tr>
<tr>
<td>IBD rate (per day)</td>
<td>714.17 \pm 4.58</td>
<td>717.86 \pm 4.60</td>
<td>532.29 \pm 3.82</td>
<td>71.78 \pm 1.29</td>
<td>69.80 \pm 1.28</td>
<td>70.39 \pm 1.28</td>
</tr>
</tbody>
</table>

171803-4
The uncertainties obtained similar results on the background and relative the combined uncertainty was 0.2%. Independent analyses recently calculated fluxes \[17,18\] (3.1% uncertainty) had little impact on the results. The thermal energy released per long-lived isotopes were applied following Ref. \[17\].

The thermal energy released per long-lived isotopes was studied using Am-C neutron data and MC at the detector center and the spallation neutron data and was determined using IBD MC. Efficiencies associated with the delayed-energy, the prompt-energy, and the capture-time cuts were evaluated with MC. Discussion of the uncertainties in the number of target protons, live time, and the efficiency of the flasher cut can be found in Ref. \[7\].

Uncorrelated relative uncertainties have been addressed in detail by performing a side-by-side comparison of two ADs \[7\]. The IBD nGd energy peaks for all six ADs were reconstructed to 8.05 ± 0.04 MeV. The relative energy scale between ADs was established by comparing the nGd peaks of the IBD- and spallation-neutrons, and α particles in the Gd-LS. Both energy-reconstruction approaches yielded a 0.5% uncorrelated energy-scale uncertainty for all six ADs. The relative uncertainty in efficiency due to the \(E_d\) cut was determined to be 0.12% using data. By measuring the difference in the neutron capture time of each AD, from which the Gd-concentration can be calculated, the relative uncertainty in the fraction of neutrons captured on Gd (the Gd capture ratio) was found to be <0.1%. All other relative uncertainties were \(0(0.01\%)\) and the combined uncertainty was 0.2%. Independent analyses obtained similar results on the background and relative uncertainties.

This analysis was independent of reactor flux models. The \(\bar{\nu}_e\) yield per fission \[12\] was not fixed when determining \(\sin^2 2\theta_{13}\). Whether we used the conventional Institut Laue-Langevin fluxes \[13-16\] (2.7% uncertainty) or the recently calculated fluxes \[17,18\] (3.1% uncertainty) had little impact on the results. The thermal energy released per fission is given in Ref. \[19\]. Nonequilibrium corrections for long-lived isotopes were applied following Ref. \[17\].

Contributions from spent fuel \[20,21\] (~ 0.3%) were included as an uncertainty.

Thermal-power data provided by the power plant carry an uncertainty of 0.5% per core \[22-24\] that we conservatively treat as uncorrelated. The fission fractions were also provided for each fuel cycle as a function of burn-up, with a ~5% uncertainty from validation of the simulation \[25,26\]. A DRAGON \[27\] model was constructed to study the correlation among the fission rates of isotopes. The uncertainties of the fission fraction simulation resulted in a 0.6% uncorrelated uncertainty of the \(\bar{\nu}_e\) yield per core. The baselines have been surveyed with a Global Positioning System and modern theodolites to a precision of 28 mm. The uncertainties in the baseline and the spatial distribution of the fission fractions in the core had a negligible effect to the results. Figure 3 presents the background-subtracted and efficiency-corrected IBD rates in the three EHs. Relative reactor flux predictions are shown for comparison.

The \(\bar{\nu}_e\) rate in the far hall was predicted with a weighted combination of the two near-hall measurements assuming no oscillation. The weights were determined by the thermal power of each reactor and its baseline to each AD. We observed a deficit in the far hall, expressed as a ratio of observed to expected events,

\[
R = 0.940 \pm 0.011(\text{stat.}) \pm 0.004(\text{syst.})
\]

In addition, the residual reactor-related uncertainties were found to be 5% of the uncorrelated uncertainty of a single core.

![FIG. 3 (color online). Daily average measured IBD rates per AD in the three experimental halls as a function of time. Data between the two vertical dashed lines were used in this analysis. The solid curves represent no-oscillation predictions based on reactor flux analyses and detector simulation for comparison. The predictions have been corrected with the best-fit normalization parameter in determining \(\sin^2 2\theta_{13}\).](image-url)
The value of $\sin^2 2\theta_{13}$ was determined with a $\chi^2$ constructed with pull terms accounting for the correlation of the systematic errors [28],

$$
\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1 + \varepsilon + \sum_r \omega^2 \alpha_r + e_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \frac{6(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2})}{(2)}
$$

where $M_d$ are the measured IBD events of the $d$th AD with backgrounds subtracted. $B_d$ is the corresponding background, $T_d$ is the prediction from neutrino flux, MC, and neutrino oscillations [29], $\omega^2$ is the fraction of IBD contribution of the $r$th reactor to the $d$th AD determined by baselines and reactor fluxes. The uncertainties are listed in Table III. The uncorrelated reactor uncertainty is $\sigma_r$ (0.8%), $\sigma_d$ (0.2%) is the uncorrelated detection uncertainty, and $\sigma_B$ is the background uncertainty listed in Table II. The corresponding pull parameters are $(\alpha_r, \varepsilon, \eta_d)$. The detector- and reactor-related correlated uncertainties were not included in the analysis; the absolute normalization $\varepsilon$ was determined from the fit to the data. The best-fit value is

$$
\sin^2 2\theta_{13} = 0.092 \pm 0.016\text{(stat.)} \pm 0.005\text{(syst.)},
$$

with a $\chi^2$/NDF of 4.26/4 (where NDF is the number of degrees of freedom). All best estimates of pull parameters are within its 1 standard deviation based on the corresponding systematic uncertainties. The no-oscillation hypothesis is excluded at 5.2 standard deviations.

The accidental backgrounds were uncorrelated while the Am-C and $(\alpha,n)$ backgrounds were correlated among ADs. The fast-neutron and $\beta^{27}$He backgrounds were site-wide correlated. In the worst case where they were correlated in the same hall and uncorrelated among different halls, we found the best-fit value unchanged while the systematic uncertainty increased by 0.001.

Figure 4 shows the measured numbers of events in each detector, relative to those expected assuming no oscillation. The 6.0% rate deficit is obvious for EH3 in comparison with the other EHs, providing clear evidence of a nonzero $\theta_{13}$. The oscillation survival probability at the best-fit values is given by the smooth curve. The $\chi^2$ versus $\sin^2 2\theta_{13}$ is shown in the inset.

The observed $\bar{\nu}_e$ spectrum in the far hall is compared to a prediction based on the near-hall measurements in Fig. 5. The disagreement of the spectra provides further evidence of neutrino oscillation. The ratio of the spectra is consistent with the best-fit oscillation solution of $\sin^2 2\theta_{13} = 0.092$ obtained from the rate-only analysis [31].

In summary, with a 43 000 ton–GW$_{th}$–day live-time exposure, 10 416 reactor antineutrinos were observed at the far hall. Comparing with the prediction based on the near-hall measurements, a deficit of 6.0% was
found. A rate-only analysis yielded $\sin^2 2\theta_{13} = 0.092 \pm 0.016^{\text{(stat.)}} \pm 0.005^{\text{(syst.)}}$. The neutrino mixing angle $\theta_{13}$ is nonzero with a significance of 5.2 standard deviations.

The Daya Bay experiment is supported in part by the Ministry of Science and Technology of China, the United States Department of Energy, the Chinese Academy of Sciences, the National Natural Science Foundation of China, the Guangdong provincial government, the Shenzhen municipal government, the China Guangdong Nuclear Power Group, Shanghai Laboratory for Particle Physics and Cosmology, the Research Grants Council of the Hong Kong Special Administrative Region of China, University Development Fund of The University of Hong Kong, the MOE program for Research of Excellence at National Taiwan University, National Chiao-Tung University, and NSC fund support from Taiwan, the U.S. National Science Foundation, the Alfred P. Sloan Foundation, the Ministry of Education, Youth and Sports of the Czech Republic, the Czech Science Foundation, and the Joint Institute of Nuclear Research in Dubna, Russia. We thank Yellow River Engineering Consulting Co., Ltd. and China railway 15th Bureau Group Co., Ltd. for building the underground laboratory. We are grateful for the ongoing cooperation from the China Guangdong Nuclear Power Group and China Light & Power Company.

*Deceased.

[29] The survival probability used in the $\chi^2$ was $P_{\text{surv}} = 1 - \sin^2 2\theta_{13}\sin^2(2\Delta m^2_{\odot}/E) - \cos^2 \theta_{13}\sin^22\theta_{13}\times \sin^2(2\Delta m^2_{\odot}/E)$, where, $\Delta m^2_{\odot} = 2.32 \times 10^{-3} \text{eV}^2$, $\sin^2 2\theta_{13} = 0.861^{+0.026}_{-0.022}$, and $\Delta m^2_{\odot} = 7.59^{+0.20}_{-0.21} \times 10^{-5} \text{eV}^2$. The uncertainty in $\Delta m^2_{\odot}$ has not been included in the fit. The fit $\sin^2 2\theta_{13}$ will change by $+0.0007$ and $-0.0004$ when $\Delta m^2_{\odot}$ changes by 1 standard deviation.
[31] Without correcting for the nonlinearity of the detector response, we have performed a preliminary shape analysis that yielded a consistent result for $\sin^2 2\theta_{13}$. 

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