Evidence of the decay $B^0 \rightarrow \eta \pi^0$

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On behalf of the Belle Collaboration
This is highly suppressed decay. Experimental determination of branching fraction and CP-violating charge asymmetries of this charmless rare decay can play an important role in testing the theoretical predictions of the Standard Model and its extension.

The branching of this decay is predicted to be in the range $(2-12) \times 10^{-7}$, estimated based on the calculations of QCDf, pQCD, SCET and SU(3) flavor symmetry.

Previous searches were performed by ARGUS, CLEO, Belle and BaBar experiments. Current PDG gives $\mathcal{B}(B^0 \rightarrow \eta \pi^0) < 1.5 \times 10^{-6}$ at 90% CL; this upper limit set by BaBar experiment.
Introduction

- We have studied the branching fraction of $B^0 \rightarrow \eta \pi^0$ decays in two different $\eta$ decay modes:
  1. $\eta \rightarrow \gamma \gamma$ and
  2. $\eta \rightarrow \pi^+ \pi^- \pi^0$

using full data set of the Belle experiment running on the $\Upsilon(4S)$ resonance at the KEKB asymmetry-energy $e^+e^-$ collider. This data set corresponds to $753 \times 10^6$ BB pairs.

- Combined branching fraction of these two sub-decay modes are obtained by performing a simultaneous fit.
Introduction

- The branching fraction of this decay is useful to constrain the isospin-breaking effects on the value of CP-violating phase $\sin 2\phi_2 (= \sin 2\alpha)$ measured in $B \rightarrow \pi\pi$ decays. [PRD 71, 074017(2005); PRD 72, 034015(2005)]

- The CKM angle $\alpha$ or $\phi_2$ is the phase difference between $V_{td}V^*_{tb}$ and $V_{ud}V^*_{ub}$ and can be extracted by measuring the time-dependent CP-violating parameters in $b \rightarrow u$ transition, with additional phase $\Delta\alpha$ is induced by $b \rightarrow d$ penguin transition. (candidates are $B \rightarrow \pi\pi$, $\pi\rho$, $\rho\rho$ decays, isospin analysis is required to extract $\alpha$)

- It can also be used to constrain CP-violating parameters governing the time-dependence of $B \rightarrow \eta'K_S$ decays. [PLB 596, 107(2004); PRD 74, 093003(2006)]
Charmless hadronic decays suffer from large background arising from continuum $e^+e^-\rightarrow qq$ (q=u,d,s,c) production.

To suppress this background, we use a multivariate analyzer based on neural network (NN).

The NN uses the event topology and B-flavor tagging information to discriminate continuum events, which tend to be jet-like, from spherical BB events.

The NN output $C_{NB}$ ranges from -1 to +1: a value closer to -1 (+1) is more likely to identify a background (signal) event.

We require $C_{NB} > -0.1$, which rejects approximately 85% of continuum background events while retaining 90% of signal events.

We use the translated NN output $C'_{NB}$ as one of the fit variable, as it can be described by a sum of Gaussian functions both for signal and background.

$$C'_{NB} = \ln \left( \frac{C_{NB} - C_{min}}{C_{max} - C_{NB}} \right)$$
Analysis technique

- A simultaneous three-dimensional fit to the variables $M_{bc}$, $\Delta E$ and $C^{'}_{NB}$ is performed to obtain the branching fraction of the decay $B^0 \rightarrow \eta \pi^0$.
- The likelihood function is defined as

$$L = e^{-\sum_j Y_j} \cdot \prod_i \left( \sum_j Y_j \mathcal{P}_j(M_{bc}^i, \Delta E^i, C_{NB}^i) \right)$$

where, $M_{bc} = \sqrt{(E_{beam})^2 - |\vec{P}_B|^2}$, and $\Delta E = E_B - E_{beam}$.

- The correlation among the fit variables are found to be small and so we factorized the PDFs as

$$\mathcal{P}_j(M_{bc}, \Delta E, C_{NB}^i) = \mathcal{P}_j(M_{bc}) \cdot \mathcal{P}_j(\Delta E) \cdot \mathcal{P}_j(C_{NB}^i).$$

- Distortion caused by this approximation is investigated by applying the fit to an ensemble of simulated experiments and are included in the systematic uncertainty.
- There are three components: signal and continuum and rare backgrounds. All components are first studied with MC simulations; high statistics control sample $B^0 \rightarrow D^0(\rightarrow K^+ \pi^- \pi^0)\pi^0$ is used to take into account the data-MC difference.

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Results

- Measured branching fraction is $\mathcal{B}(B^0 \rightarrow \eta \pi^0) = [4.1(\pm 1.7 \pm 0.5, \pm 1.5 - 0.7)] \times 10^{-7}$ with a total significance of 3.0 standard deviations. Therefore, our measurement constitutes the first evidence for this decay mode.

- As the total significance is at its marginal point, we also give the upper limit (Bayesian), obtained by integrating the likelihood function from zero to infinity; the value corresponds to 90% of this total area is taken as the 90% CL upper limit, which is $\mathcal{B}(B^0 \rightarrow \eta \pi^0) < 6.5 \times 10^{-7}$.

See arXiv:1504.00957[hep-ex] (submitted to PRD) for details!
Non-resonant contributions?

- Non-resonant decay can pollute the decay.
- To check the potential non-resonant contributions, we relax the $\eta$ mass requirement and plot the $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ invariant mass distributions for events in the $M_{bc}\Delta E$ signal region.

This is also checked quantitatively, by applying the fitter in $\eta$ sidebands. We obtain $2.2(+4.8,-3.3)$ events for (a) and $-2.2(+3.4,-2.5)$ events for (b): both are consistent with zero. To be conservative, we assign a systematic uncertainty by appropriately scaling this fit result.
TABLE II. Systematic uncertainties on $B(B^0 \rightarrow \eta \pi^0)$. Those listed in the upper section are associated with fitting for the signal yields and are included in the signal significance and upper limit calculation.

<table>
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<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
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<tr>
<td>PDF parametrization</td>
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<td></td>
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<tr>
<td>Fit bias</td>
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<tr>
<td></td>
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<td>$\pi^0/\eta \rightarrow \gamma \gamma$ reconstruction</td>
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<tr>
<td>PID efficiency</td>
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<tr>
<td>$C_{NB}$ selection efficiency</td>
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<td></td>
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<td>MC statistics</td>
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<tr>
<td>Nonresonant contributions</td>
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<tr>
<td></td>
<td>-10.8</td>
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<tr>
<td>$B(\eta \rightarrow \gamma \gamma)$</td>
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</tr>
<tr>
<td>$B(\eta \rightarrow \pi^+\pi^-\pi^0)$</td>
<td>1.2</td>
</tr>
<tr>
<td>Number of $B\bar{B}$ pairs</td>
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</tr>
<tr>
<td>Total</td>
<td>+12.2</td>
</tr>
<tr>
<td></td>
<td>-15.9</td>
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</table>
Isospin-breaking correction

- Isospin-breaking in $B \rightarrow \pi\pi$ decays caused by $\pi^0$-$\eta$-$\eta'$ mixing is studied in (1) PRD 71, 074017 (2005) and (2) PRD 72, 034015 (2005).
- In Ref (1), the isospin-breaking correction due to $\pi^0$-$\eta$-$\eta'$ mixing to the value of weak phase $\phi_2(\equiv \alpha)$ measured in $B \rightarrow \pi\pi$ decays is found to be

$$|(\Delta \alpha - \Delta \alpha_0)_{\pi^0-\eta-\eta'}| < 1.6^\circ \text{ at 90\% CL.}$$

- By replacing $\mathcal{B}(B^0 \rightarrow \eta\pi^0)$ with our measurement in their calculation, one obtains

$$|(\Delta \alpha - \Delta \alpha_0)_{\pi^0-\eta-\eta'}| < 0.97^\circ \text{ at 90\% CL,}$$

which is about 40\% improvement on this value.
- This bound can be further improved by few more \%, if we use recent PDG averages for $\mathcal{B}(B^0 \rightarrow \eta\pi^0)$, $\mathcal{B}(B^+ \rightarrow \pi^+\pi^0)$ and $\tau_{B^+}/\tau_{B^0}$. 

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B^0 \rightarrow \pi^0 \pi^0 \ (Belle \ preliminary)

- Similar tree and penguin diagrams contribute as of \(B^0 \rightarrow \eta \pi^0\)

Theory (QCDF) [PRD 83, 034023(2011)] predicts the Branching fraction of this decay mode <1×10^{-6}

\[\Gamma(B^0 \rightarrow \pi^0 \pi^0) / \Gamma_{total}\]

<table>
<thead>
<tr>
<th>Value (10^{-6})</th>
<th>CL%</th>
<th>Document ID</th>
<th>TECN</th>
</tr>
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<td>1.91 \pm 0.22</td>
<td>1.83 \pm 0.21 \pm 0.13</td>
<td>LEES</td>
<td>2013D</td>
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<tr>
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<td>1</td>
<td>CHAO</td>
<td>2005</td>
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</table>

- (Belle preliminary results)

\[\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) = (0.89 \pm 0.12 \pm 0.10) \times 10^{-6}\]

(significance) = 7.1\sigma

\[A_{CP} = -0.38 \pm 0.36 \pm 0.03\]
Constraints on $\phi_2(\equiv \alpha)$

- Combining our newly measured $\text{Br}$ and $A_{\text{CP}}$ of $B^0 \rightarrow \pi^0\pi^0$ with our previous measurement of $\text{Br}$ and time-dependent CPV for $B^0 \rightarrow \pi^+\pi^-$ [PRD 88, 092003(2013)] and $\text{Br}$ and $A_{\text{CP}}$ of $B^+ \rightarrow \pi^0\pi^+$ [PRD 87, 031103(R) (2012)] allow us to employ an isospin analysis to constrain $\phi_2(\equiv \alpha)$
- Excluded regions at 1 sigma confidence are $5^\circ < \alpha < 85^\circ$ and $190^\circ < \alpha < 225^\circ$

Current PDG average $\alpha = (90\pm 5)^\circ$

Red represent the previous constraint from Belle
Blue include the newly measured $\text{Br}$ and $A_{\text{CP}}$ of $B^0 \rightarrow \pi^0\pi^0$
We have studied the decay $B^0 \rightarrow \eta \pi^0$ at Belle.

We measured the branching fraction

$$B(B^0 \rightarrow \eta \pi^0) = (4.1^{+1.7+0.5}_{-1.5-0.7}) \times 10^{-7}.$$  

The total significance of the decay including the systematic uncertainties is found be 3.0 standard deviations, which constitutes the first evidence for this decay mode.

Our measured branching fraction improves the isospin-breaking correction due to $\pi^0$-$\eta$-$\eta'$ mixing to the value of weak phase $\phi_2(\equiv \alpha)$ measured in $B \rightarrow \pi \pi$ decays by about 40%.

We have also preliminary result on the $\text{Br}$ and $A_{CP}$ of the decay $B^0 \rightarrow \pi^0 \pi^0$ which are $\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) = (0.89\pm0.12\pm0.10)\times10^{-6}$ and $A_{CP} = -0.38\pm0.36\pm0.03$.

Isospin analysis of $B \rightarrow \pi \pi$ in Belle excludes $5^\circ < \alpha < 85^\circ$ and $190^\circ < \alpha < 225^\circ$.

Thank you
M. GRONAU AND J. ZUPAN

\[
|\Delta \alpha - \Delta \alpha_0|_{\pi^- \eta^- \eta'} \leq \epsilon \left( \frac{A_{0\eta} + A_{0\eta'}}{\sqrt{2}|A_{+0}|} \right) \\
+ \epsilon' \left( \frac{|A_{0\eta'}| + |A_{0\eta}|}{\sqrt{2}|A_{+0}|} \right) \\
\leq \sqrt{\frac{\tau_+}{\tau_0}} \left( \epsilon \sqrt{\frac{B_{0\eta}}{B_{+0}}} + \epsilon' \sqrt{\frac{B_{0\eta'}}{B_{+0}}} \right). 
\]

(19)

Here \( B_{ij} = (|A_{ij}|^2 + |\tilde{A}_{ij}|^2)\tau_\nu/2 \) denote charge-averaged branching ratios for corresponding decays, and \( \tau_+ / \tau_0 \) is the lifetime ratio of \( B^+ \) and \( B^0 \). We neglect tiny corrections (at a level of a percent) in phase space factors.

Using world averaged values [33–37],

\[
\frac{\tau_+}{\tau_0} = 1.081 \pm 0.015, \quad B_{+0} = (5.5 \pm 0.6) \times 10^{-6},
\]

\[
B_{0\eta} < 2.5 \times 10^{-6} (90\% \text{ CL}), \quad B_{0\eta'} < 3.7 \times 10^{-6} (90\% \text{ CL})
\]

(20)

we find at 90% CL

\[
|\Delta \alpha - \Delta \alpha_0|_{\pi^- \eta^- \eta'} < 1.05 \epsilon + 1.28 \epsilon' = 1.6^\circ. 
\]

(21)
Belle experiment

- Belle spectrometer is a high resolution $4\pi$ spectrometer with particle identification capability, optimized to study the flavor physics.
- Operating at KEKB asymmetric-energy $e^+e^-$ collider.
- 10.58 GeV Center of Mass energy at $\Upsilon(4S)$ resonance, suitable for BB production.
- Total integrated luminosity collected: $1000 \text{ /fb}$