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Search for the Familon via $B^{\pm} \to \pi^{\pm} X^0$, $B^{\pm} \to K^{\pm} X^0$, and $B^0 \to K^0_S X^0$ Decays

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Abstract

We have searched for the two-body decay of the B meson to a light pseudoscalar meson $h = \pi^{\pm}, K^{\pm}, K^0_S$ and a massless neutral weakly-interacting particle X^0 such as the familon, the Nambu-Goldstone boson associated with a spontaneously broken global family symmetry. We find no significant signal by analyzing a data sample containing 9.7 million $B\bar{B}$ mesons collected with the CLEO detector at the Cornell Electron Storage Ring, and set a 90% C.L. upper limit of 4.9×10^{-5} and 5.3×10^{-5} on the branching fraction for the decays $B^{\pm} \to h^{\pm} X^0$ and $B^0 \to K^0_S X^0$, respectively. These upper limits correspond to a lower bound of $\approx 10^8$ GeV on the family symmetry breaking scale involving the third generation of quarks.

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The origin of family replication remains one of the major puzzles in particle physics. Why do we have three families of fermions, which are indistinguishable with respect to the strong and electroweak interactions? Neither the Standard Model (even incorporating the Higgs mechanism) nor its extension by various unification schemes in the framework of one family (SU(5), SO(10)) is able to provide a deep physical reason for the existence of the mass hierarchy among the generations and the weak mixing of quarks and leptons. In the absence of a concrete model, it is natural to assume that the underlying theory possesses a "horizontal" family symmetry which is spontaneously broken at some large energy scale. Among several possibilities, the most attractive is the assumption of a global (and continuous) flavor symmetry [1]. This symmetry, under some conditions [3], automatically induces the Peccei-Quinn symmetry [4], and thus provides a solution for the strong CP problem. The spontaneous symmetry breaking of a continuous and global family symmetry implies the existence of neutral massless Nambu-Goldstone bosons [5], called familons, which can have flavor-conserving as well as flavor-changing couplings with the fermions [1,2].

Flavor-changing couplings between the familon and fermions induce decays, such as $K^+ \to \pi^+ X^0$ or $\mu^+ \to e^+(\gamma)X^0$, that have been studied experimentally [6,7]. Upper limits on the rate of these decays led to the lower bounds on the family symmetry breaking scale involving the first two generations: $\approx 10^{11}$ GeV and $\approx 10^9$ GeV in the hadronic and the leptonic sector, respectively. In contrast, bounds on the flavor scale involving the third generation are less thoroughly studied experimentally, although, some theoretical models suggest that the familon couples preferentially to the third generation [8]. The upper limits for $\tau \to \ell X^0$ ($\ell = e, \mu$) [9] led to a lower bound on the family symmetry breaking scale $F \gtrsim 10^6$ GeV in the leptonic sector, and no bounds have been reported in the hadronic sector.

Familon couplings to the third generation are also of interest from a cosmological point of view. A massive unstable neutrino (typically the tau-neutrino) was proposed to decay into a lighter neutrino and a massless boson, such as a familon, in several cosmological scenarios related to big-bang nucleosynthesis [10], and large scale structure formation [11], in order to obtain a reasonable agreement between theory and observation. Since the process $\nu_\tau \to \nu_l f$ is related to the decay modes $\tau \to \ell f$ and $b \to q_d f$ ($q_d = d, s$) through $SU(2)_L$ and SU(5) GUT gauge symmetries, searches for the latter decay modes can test the cosmological scenarios as well [2].

The decay of the b quark $b \to q_d f$ would lead to the decay $B \to hf$ ($h = \pi, K$) through vector coupling and $B \to Vf$ ($V = \rho, K^*$) through axial coupling, respectively. The purpose of this study is to search for the $B^\pm \to h^\pm X^0$ and $B^0 \to K_S^0 X^0$ decays, where X^0 is any neutral massless weakly-interacting particle including the familon, using the CLEO data set. The lack of a signal allows us to obtain a constraint on the vector coupling of the familon to third generation hadrons for the first time. (The analysis is sensitive to new physics including massless weakly-interacting neutral particles as well.) The partial width Γ of the decay is related to the family symmetry breaking scale F through the formula

$$\Gamma(B \to hf) = \frac{M_B^3}{16\pi}\left(1 - \frac{m_h^2}{M_B^2}\right)^3 \frac{g_V^2 T_{bd(s)}^2}{F^2} \mid F_1(0) \mid^2, \tag{1}$$

where M_B, m_h are the masses of the mesons involved in the decay process, g_V is the vector type coupling constant, $T_{bd(s)}$ are the generators of the broken symmetry, and $F_1(0)$ is the form factor [2].

The data analyzed in this study were collected with the CLEO detector at the Cornell Electron Storage Ring (CESR), a symmetric e^+e^- collider. The components of the detector [12] most relevant to this analysis are the charged particle tracking system, the CsI electromagnetic calorimeter, and the muon detector. Trajectories of charged particles were reconstructed using a system of three concentric wire chambers (a 6-layer straw tube chamber, a 10-layer precision drift chamber, and a 51-layer main drift chamber) covering 95% of the total solid angle, operating in an axial solenoidal magnetic field of 1.5 T. The main drift chamber also provided a measurement of the specific ionization loss (dE/dx) used for particle identification. Photons were detected by a CsI(Tl) electromagnetic calorimeter covering 98% of 4π. The muon chambers consisted of proportional counters embedded at various depths in the steel absorber. Approximately 2/3 of the data were collected with an upgraded detector, in which the innermost straw tube chamber was replaced with a three-layer, double-sided silicon vertex detector [13], and the gas in the main drift chamber was changed from an argon-ethane to a helium-propane mixture. These modifications led to an improved particle identification and momentum resolution.

The results in this Letter are based upon an integrated luminosity of 9.2 fb^{-1} of e^+e^- data corresponding to 9.7 million $B\bar{B}$ meson pairs collected at the Υ(4S) resonance energy of 10.58 GeV ("on-resonance sample") and 4.6 fb^{-1} at 60 MeV below the Υ(4S) resonance ("off-resonance sample"). The study of the off-resonance sample enables us to statistically subtract the continuum ($e^+e^- \to q\bar{q}$, $q = u, d, c, s$) background contribution from the on-resonance sample. In order to study signal reconstruction efficiency and to optimize selection criteria we generated Monte Carlo simulated samples with a GEANT-based [14] simulation of the CLEO detector response. Simulated data samples were processed in a similar manner as the data.

The experimental signature of the the $B^\pm \to h^\pm X^0$ and $B^0 \to K^0_S X^0$ decays is that the familon as a neutral very weakly-interacting particle escapes from the detector without any trace and only its light meson partner can be observed. Due to the two-body decay structure, the meson partner is produced with a well defined momentum of 2.65 GeV/c in the center of mass frame of the decaying B meson. However, in the lab frame its momentum is spread between $2.49 - 2.80$ GeV/c due to Doppler broadening. Other detected particles and photons must be coming from the decay of the other B meson. Our analysis strategy to search for these decay modes is the following: (1) we select events with a well identified light meson having a momentum in the expected range while (2) all remaining particles must be consistent with the decay of a second B meson, and (3) eliminate as much continuum background as possible.

Candidates for the $\pi^\pm$ or $K^\pm$ meson partner of the familon ("meson candidate") were selected from well-reconstructed tracks originating near the e^+e^- interaction point (IP). Since charged π and K meson separation in the momentum range expected is difficult with the CLEO detector, we combined the charged B decay modes by requiring the charged meson candidate's dE/dx to be consistent with either the pion or the kaon hypothesis within 2.5 standard deviation (σ). We rejected electrons based on dE/dx and the ratio of the track momentum to the associated shower energy deposited in the CsI calorimeter. Muons were rejected based on the penetration depth in the steel absorber surrounding the detector. The K^0_S candidates were reconstructed via their decay into $\pi^+\pi^-$ by requiring a decay vertex displacement from the IP and an invariant $\pi\pi$ mass within 10 MeV/c^2 of the known K_S^0 mass. We accepted meson candidates with momentum in the range $2.49 < p_{h^\pm} < 2.81$ GeV/c or $2.47 < p_{K_S^0} < 2.79$ GeV/c. These and other selection criteria were optimized by maximizing the signal significance, $S^2/(S+B)$, where S and B, the expected signal and background level was determined from Monte-Carlo simulated samples assuming a signal branching fraction of 10^{-5}.

Since the remaining particles in the event must originate from the decay of the second B meson we required that the beam constrained mass, $M(B) = \sqrt{E_{\rm beam}^2 - (\sum \mathbf{p}_i)^2}$, be close to the B meson mass and the energy difference, $\Delta E = \sum E_i - E_{\rm beam}$, be close to zero, where E_i and $\mathbf{p}_i$ are the energy and momentum of all detected particles in the event except for the meson candidate. The optimization of the selection criteria on the $M(B)$ and ΔE variables resulted in $M(B) > 5.245$ GeV/c^2 ($M(B) > 5.24$ GeV/c^2) and $-2.1 < \Delta E < 0.3$ GeV ($-3.0 < \Delta E < 0.4$ GeV) limits for the charged (neutral) B decay mode.

The main contribution to the background comes from continuum events. These events typically exhibit a two-jet structure and produce high momentum back-to-back tracks, while $B\bar{B}$ events tend to have a more isotropic decay structure, since the B mesons are produced nearly at rest ($P_B \approx 0.32$ GeV/c). We used the Fisher discriminant technique [15] to reduce the continuum background. The Fisher discriminant was formed as the linear combination of 14 shape variables: 9 momentum flow variables (the sum of the momentum of all detected particles in 10^o angular bins around the direction of the meson candidate); the angle between the momentum of the other B meson reconstructed from the rest of the event and the e^+e^- collision ("beam") axis; the angle between the momentum of the meson candidate and the beam axis; the second order normalized Fox-Wolfram moment [16]; the angle between the momentum of the meson candidate and the thrust axis of the rest of the event; and the maximum opening angle of the cone opposite to the momentum of the meson candidate, in which no other charged track, π^0 or K_S^0 was detected. The combination coefficients were chosen to maximize the separation between the simulated signal and continuum background samples.

The distribution of the Fisher discriminant used in the charged B analysis is shown for simulated events and off-resonance data on Fig. 1. The agreement between simulated continuum and off-resonance events is very good. We selected candidate events with a Fisher discriminant less than -0.4 in case of the charged B decay mode, and less than 1.0 for the neutral B decay mode.

The overall signal selection efficiency is 7.2% for $B^\pm \to h^\pm X^0$ and 6.6% for the $B^0 \to K_S^0 X^0$ events. The systematic error on the efficiency is 13% (18%) for the charged (neutral) B decay mode. The contributions to this error are due to the uncertainties in the tracking efficiency, 2% (4%), the momentum selection, 1% (1%), $M(B)$ and ΔE selection, 6% (6%), Fisher discriminant restriction, 11% (16%), and limited Monte Carlo statistics, 1% (1%).

Table I lists the number of events passing the consecutive selection requirements in the data and simulated signal samples. Figure 2 shows the momentum distribution of the meson candidate for on-resonance and off-resonance events along with the distributions for simulated events after all selection criteria except the tight momentum restriction on the meson candidate were applied. The number of on-resonance (off-resonance) events in the selected momentum range is 74 (32) in case of the $B^\pm \to h^\pm X^0$ and 44 (14) in case of the $B^0 \to K_S^0 X^0$

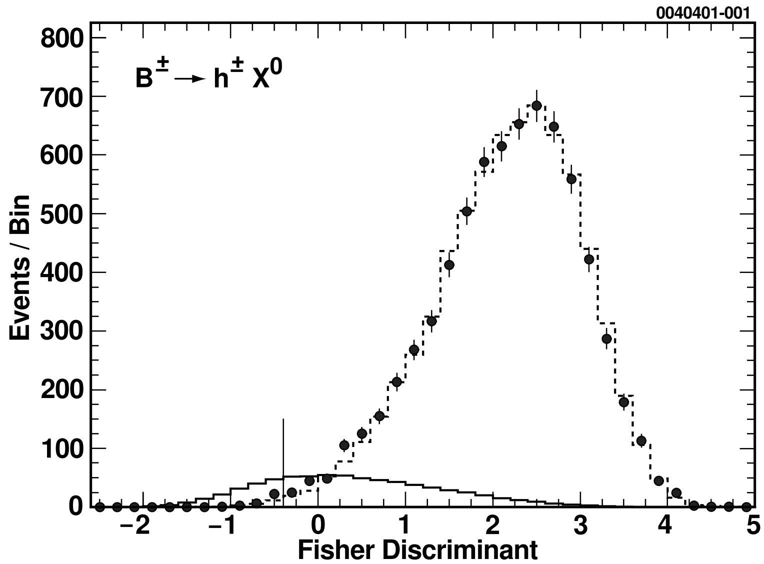

FIG. 1. Distribution of the Fisher discriminant used in the $B^{\pm} \to h^{\pm}X^0$ analysis for simulated signal (solid) and continuum (dashed) as well as off-resonance data (points) samples. The histograms are normalized to the statistics of the off-resonance data. The signal histogram is plotted assuming a branching ratio of 50×10^{-5}. The vertical line represents the optimum selection value below which events were accepted.

analysis. The study of the background from $b \to c$, and other rare $b \to u$ and $b \to s$ decays as well as from tau decays using simulated data samples showed these to be negligible.

We calculated the branching fraction based on

$$\mathcal{B} = \frac{N_{\rm on} - RN_{\rm off}}{\epsilon N_B}, \tag{2}$$

where $N_{\rm on}$ and $N_{\rm off}$ are the observed events in the signal region in the on-resonance and off-resonance data samples, respectively, $R(= 2.0)$ is the normalization coefficient between the two samples, ϵ is the signal selection efficiency, and N_B is the total number of charged (neutral) B mesons in the data sample, assuming equal production of charged and neutral B meson pairs from the $\Upsilon(4S)$ [17]. We find $\mathcal{B}(B^{\pm} \to h^{\pm}X^0) = (1.4 \pm 2.1) \times 10^{-5}$ and

TABLE I. Number of events passing each consecutive selection criteria in on-resonance, off-resonance data and simulated signal samples.

	$B^{\pm} \to h^{\pm}X^0$			$B^0 \to K^0_S X^0$		
	On-res.	Off-res.	MC Signal	On-res.	Off-res.	MC Signal
Total events	57 million	23 million	180,000	57 million	23 million	90,000
Pre-selected events	157,919	73,671	90,211	64,207	31,230	36,953
Momentum selection	41,981	20,437	83,592	18,675	9,224	34,720
M_B and ΔE selection	14,243	7,073	55,024	2,330	1,135	17,725
Fisher selection	74	32	12,896	44	14	5,973

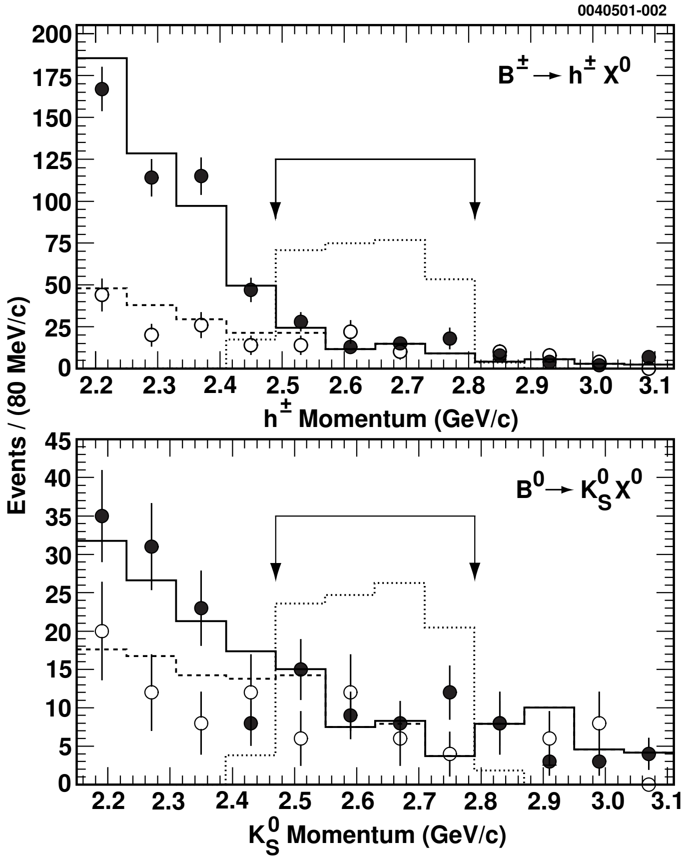

FIG. 2. Momentum distribution of the meson candidates. Filled and empty dots represent the on-resonance and the normalized off-resonance data, respectively. Solid histogram shows the prediction from $e^+e^- \to q\bar{q}$ plus $b \to c$ simulations while the dashed histogram shows the distribution from $e^+e^- \to q\bar{q}$ only. These histograms are normalized to the statistics of our data sample. Simulated signal events are shown by the dotted histogram assuming that $\mathcal{B}(B^{\pm} \to h^{\pm}X^0) \approx 30 \times 10^{-5}$ and $\mathcal{B}(B^0 \to K^0_S X^0) \approx 12 \times 10^{-5}$. The accepted signal region is indicated by the arrows.

$\mathcal{B}(B^0 \to K^0_S X^0) = (2.5 \pm 1.7) \times 10^{-5}$. The error in the branching fraction is dominated by the statistical error in $N_{\rm on}$ and $N_{\rm off}$. We derived a 90% confidence level upper limit based on the frequentist approach applied for Gaussian data close to a physical boundary [18]: $\mathcal{B}(B^{\pm} \to h^{\pm}X^0) < 4.9 \times 10^{-5}$ and $\mathcal{B}(B^0 \to K^0_S X^0) < 5.3 \times 10^{-5}$.

The upper limits can be converted into a lower bound on the family symmetry breaking scale, $F^V_{bs(d)} = F/(g^V T_{bs(d)})$, with vector-like coupling between the familon and the quarks using Eq. 1. To do so we take the form factor $F_1(0)$ to be 0.25 from a sum rules calculation [19]. The upper limit on the branching fraction of $B^0 \to K^0_S X^0$ gives $F^V_{bs} \gtrsim 6.4 \times 10^7$ GeV. The other limit gives a slightly better bound of $F^V_{bs(d)} \gtrsim 1.3 \times 10^8$ GeV with the assumption that the familon couples to the d and s quark with approximately the same strength ($F_{bs} \approx F_{bd}$).

In conclusion, we performed a search for the decays $B^{\pm} \to h^{\pm}X^0$ and $B^0 \to K^0_S X^0$, setting upper limits for the branching fractions at 4.9×10^{-5} and 5.3×10^{-5} respectively.

These limits constrain new physics leading to two-body B decays involving any massless neutral weakly-interacting particle X^0. Applying the limit to the case where X^0 is a familon, we obtain the first lower bound on the family symmetry breaking scale involving the third generation of quarks at 10^8 GeV.

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