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A study of radiative bottomonium transitions using converted photons

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We use (111 ± 1) million $\Upsilon(3S)$ and (89 ± 1) million $\Upsilon(2S)$ events recorded by the *BABAR* detector at the PEP-II B-factory at SLAC to perform a study of radiative transitions between bottomonium states using photons that have been converted to e^+e^- pairs by the detector material. We observe $\Upsilon(3S) \to \gamma\chi_{b0,2}(1P)$ decay, make precise measurements of the branching fractions for $\chi_{b1,2}(1P,2P) \to \gamma\Upsilon(1S)$ and $\chi_{b1,2}(2P) \to \gamma\Upsilon(2S)$ decays, and search for radiative decay to the $\eta_b(1S)$ and $\eta_b(2S)$ states.

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I. INTRODUCTION

Bottomonium spectroscopy and radiative transitions between $b\bar{b}$ states can be well-described by effective potential models [1]. To leading order, radiative decays are expected to be dominantly electric (E1) or magnetic (M1) dipole transitions. In the non-relativistic limit, theoretical predictions for these decays are straightforward and well-understood. However, there are a few notable cases where the non-relativistic decay rates are small or zero, *e.g.* in "hindered" M1 transitions between S-wave bottomonium such as $\Upsilon(nS) \to \gamma\eta_b(n'S)$ $(n > n')$, and as a consequence of small initial- and final-state wavefunction overlap in the case of $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ decays [16]; higher-order relativistic and model-dependent corrections then play a substantial role. Measurements of these and other E1 transition rates can lead to a better understanding of the relativistic contributions to, and model dependencies of, interquark potentials. Furthermore, because radiative transitions have a distinct photon energy signature associated with the mass difference between the relevant $b\bar{b}$ states, they are useful in spectroscopic studies for mass measurements, and in the search for and identification of undiscovered resonances.

Radiative transitions within the bottomonium system have been studied previously in several experiments, such as Crystal Ball [2, 3], ARGUS with converted photons [4], and iterations of CUSB [5–9] and CLEO [10–14] (including an analysis of photon pair conversions in a lead radiator inserted specifically for that purpose [15]). These analyses have focused mainly on $\chi_{bJ}(nP)$-related mea-

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[§] Also with Università di Sassari, Sassari, Italy surements, such as the determination of the masses and the E1 transition rates to and from $\Upsilon(mS)$ states. More recently, the *BABAR* experiment finished its operation by collecting large samples of data at the $\Upsilon(3S)$ and $\Upsilon(2S)$ center-of-mass (CM) energies. These data are useful for studies of bottomonium spectroscopy and decay and have already led to the discovery of the long-sought $\eta_b(1S)$ bottomonium ground state [17, 18], an observation later confirmed by CLEO [19].

In this paper, we present a study of radiative transitions in the bottomonium system using the inclusive converted photon energy spectrum from $\Upsilon(3S)$ and $\Upsilon(2S)$ decays. The rate of photon conversion and the reconstruction of the resulting e^+e^- pairs has a much lower detection efficiency than that for photons in the *BABAR* electromagnetic calorimeter, a disadvantage offset by a substantial improvement in the photon energy resolution. This improvement in resolution is well-suited for performing precise transition energy (hence, particle mass, and potentially width) measurements, and to disentangle overlapping photon energy lines in the inclusive photon energy spectrum. This analysis has different techniques, data selection, and systematic uncertainties than the previous studies [17–19], and is relatively free from complications due to overlapping transition peaks, and calorimeter energy scale and measurement uncertainties. We report measurements of $\chi_{bJ}(2P) \to \gamma\Upsilon(2S)$, $\chi_{bJ}(1P, 2P) \to \gamma\Upsilon(1S)$, observation of $\Upsilon(3S) \to \gamma\chi_{b0,2}(1P)$, and searches for the $\eta_b(1S, 2S)$ states.

In Sec. II we describe the *BABAR* detector and the data samples used in this analysis. Section III describes the photon conversion reconstruction procedure and the event selection criteria. Each of the following sections (Sec. IV - VII) individually describes the analysis of a particular region of interest in the inclusive photon energy spectrum. Section VIII summarizes the results obtained.

II. THE *BABAR* DETECTOR AND DATA SAMPLES

The *BABAR* detector is described in detail elsewhere [20]; a brief summary is provided here. Moving outwards from the collision axis, the detector consists of a double-sided five-layer silicon vertex tracker (SVT) for measuring decay vertices close to the interaction point (IP), a 40-layer drift chamber (DCH) for charged-particle tracking and momentum measurement, a ring-imaging Cherenkov detector for particle identification, and a CsI(Tl) crystal electromagnetic calorimeter (EMC) for measuring the energy deposited by electrons and photons. These detector subsystems are contained within a large solenoidal magnet which generates a 1.5-T field. The steel magnetic flux return is instrumented with a muon detection system consisting of resistive plate chambers and limited streamer tubes [21].

The inner tracking region also contains non-instrumented support structure elements. Interior to the SVT, the interaction region is surrounded by a water-cooled, gold-coated beryllium beam pipe. The SVT support structure consists primarily of carbon-fiber and Kevlar®. The SVT, beam pipe and vacuum chamber, and the near-IP magnetic elements are mounted inside a cylindrical, carbon-fiber support tube. The inner wall of the DCH is a cylindrical tube of beryllium coated with anti-corrosion paint. A photon at normal incidence traverses approximately 0.01 radiation lengths (X_0) of material before reaching the SVT, and an additional $0.03X_0$ before the DCH. Due to the asymmetric energy of the incoming e^+e^- beams, the photons in this analysis tend to be boosted in the direction of e^- beam, increasing the typical number of radiation lengths up to $0.02X_0$ and $0.08X_0$ to reach the previously noted detector subsystems. While this extra material is usually considered detrimental to detector performance, it is essential for $\gamma \to e^+e^-$ conversions in the present analysis.

The *BABAR* detector collected data samples of (121 ± 1) million $\Upsilon(3S)$ and (98 ± 1) million $\Upsilon(2S)$ decays [22] produced by the PEP-II asymmetric energy e^+e^- collider. This corresponds to an integrated luminosity of 27.9 ± 0.2 fb^{-1} (13.6 ± 0.1 fb^{-1}) taken at the $\Upsilon(3S)$ ($\Upsilon(2S)$) resonance. Approximately 10% of these data (referred to here as the "test sample") were used for feasibility studies and event selection optimization; they are excluded in the final analysis. The results presented in this analysis are based on data samples of (111 ± 1) million $\Upsilon(3S)$ and (89 ± 1) million $\Upsilon(2S)$ decays. An additional 2.60 ± 0.02 (1.42 ± 0.01) fb^{-1} of data were taken at a CM energy approximately 30 MeV below the nominal $\Upsilon(3S)$ ($\Upsilon(2S)$) resonance energy, to be used for efficiency-related studies.

Large Monte Carlo (MC) datasets simulating the signal and expected background decay modes are used for the determination of efficiencies and the parameterization of lineshapes for signal extraction. The particle production and decays are simulated using a combination of EVTGEN [23] and JETSET [24]. The radiative decays involving $\chi_{bJ}(nP)$ states are assumed to be dominantly E1 radiative transitions, and the MC events are generated with theoretically predicted helicity amplitudes [25]. The interactions of the decay products traversing the detector are modeled by Geant4 [26].

III. EVENT RECONSTRUCTION AND SELECTION

Photon conversions are reconstructed with a dedicated fitting algorithm that pairs oppositely charged particle tracks to form secondary vertices away from the interaction point. The algorithm minimizes a χ^2 value (χ^2_{fit}) based on the difference between the measured helical track parameters and those expected for the hypothesis that the secondary vertex had originated from two nearly parallel tracks emitted from a $\gamma \to e^+e^-$ conver-

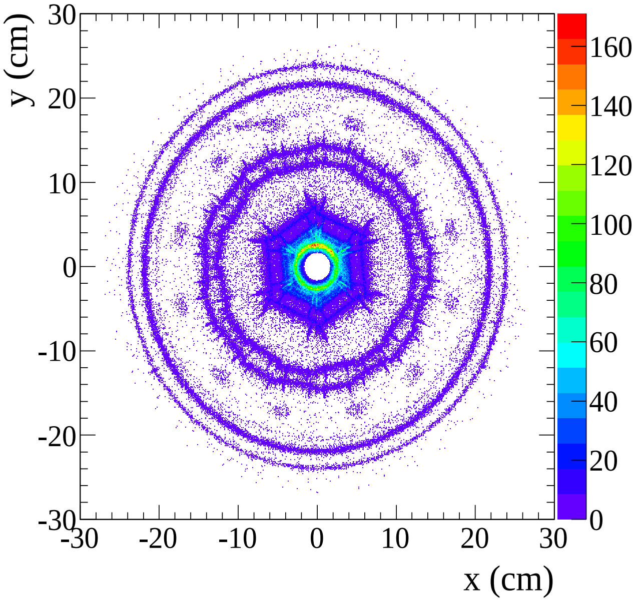

FIG. 1: (Color online) End view of the the *BABAR* inner detector along the beam axis as seen by converted photons. Points indicate the number of converted photon vertices per cross-sectional area, as measured in a subset of the "test sample" data. From the center outwards, features of note include the beam pipe, the SVT (*e.g.* hexagonal inner layers) and its support structure rods, the support tube, and the inner wall of the DCH.

sion. The χ^2_{fit} value includes a term to account for an observed finite opening angle between the converted tracks. Requiring $\chi^2_{fit} < 34$ is found to be the optimal value to select a high-purity converted photon sample. The reconstructed converted photons are also required to have an e^+e^- invariant mass of $m_{e^+e^-} < 30\,\mathrm{MeV}/c^2$ (though in practice, $m_{e^+e^-}$ is typically less than $10\,\mathrm{MeV}/c^2$). To remove internal conversions and Dalitz decays, and to improve signal purity, the conversion vertex radius (ρ_γ) is required to satisfy $1.7 < \rho_\gamma < 27$ cm. This restricts the photon conversions to the beampipe, SVT, support tube, and inner wall of the DCH, as seen in the plot of conversion vertex position for a portion of the "test sample" in Fig. 1. The efficiency for photon conversion and reconstruction versus energy in the CM frame (E^*_γ), as determined from a generic $\Upsilon(3S)$ MC sample, is shown in Fig. 2.

Figure 3 shows the inclusive distributions of the resulting reconstructed converted photon energy. The data are divided into four energy ranges, as indicated by the shaded regions in Fig. 3. These ranges and the corresponding bottomonium transitions of interest are, in $\Upsilon(3S)$ data:

- $180 \leq E^*_\gamma \leq 300\,\mathrm{MeV}$: $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)$
- $300 \leq E^*_\gamma \leq 600\,\mathrm{MeV}$: $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(1P)$ and $\Upsilon(3S) \rightarrow \gamma\eta_b(2S)$

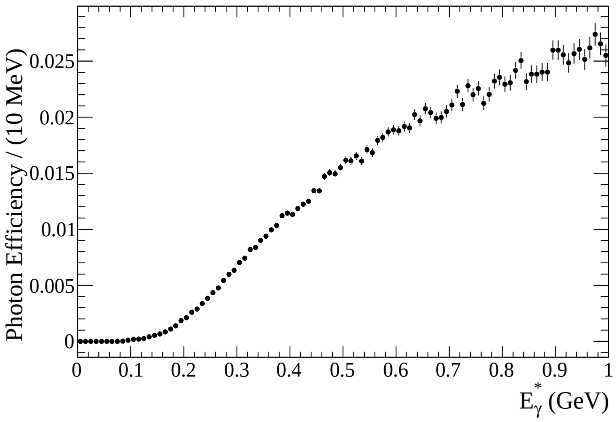

FIG. 2: Efficiency for the conversion and reconstruction of a photon versus photon energy as derived from a sample of generic $\Upsilon(3S)$ MC before the optimal selection criteria have been applied.

- $600 \leq E^*_\gamma \leq 1100\,\mathrm{MeV}$: $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$ and $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$

and in $\Upsilon(2S)$ data:

- $300 \leq E^*_\gamma \leq 800\,\mathrm{MeV}$: $\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$ and $\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$.

Peaks related to some of these transitions are already clearly visible in Fig. 3, where the photon energy in the CM frame of the initial particle for the radiative transition from an initial (i) to final (f) state is given in terms of their respective masses by

$$E_\gamma(i \rightarrow f) = \frac{m_i^2 - m_f^2}{2m_i}c^2. \qquad (1)$$

Because we analyse the photon energy in the CM frame of the initial $\Upsilon(mS)$ system (E^*_γ), the photon spectra from subsequent boosted decays (*e.g.* $\chi_{bJ}(nP) \rightarrow \gamma\Upsilon(1S)$) are affected by Doppler broadening due to the motion of the parent state in the CM frame.

To best enhance the number of signal (S) to background (B) events, the event selection criteria are chosen by optimizing the figure of merit $\mathcal{F} = \frac{S}{\sqrt{S+B}}$. This is done separately for each energy region. The $180 \leq E^*_\gamma \leq 300\,\mathrm{MeV}$ energy region in $\Upsilon(3S)$ uses the same criteria as determined for the similarly low energy $300 \leq E^*_\gamma \leq 600\,\mathrm{MeV}$ range. We determine S from MC samples of $\Upsilon(mS) \rightarrow \gamma\eta_b(1S)$ weighted to match the measured branching fractions [27], and $\Upsilon(3S) \rightarrow \gamma\eta_b(2S)$ assuming the same branching fraction as for the decay to $\gamma\eta_b(1S)$. The "test sample" data are used to estimate B. The optimization is performed by varying the selection criteria for the total number of tracks in the event ($nTRK$), the absolute value of the cosine of the angle

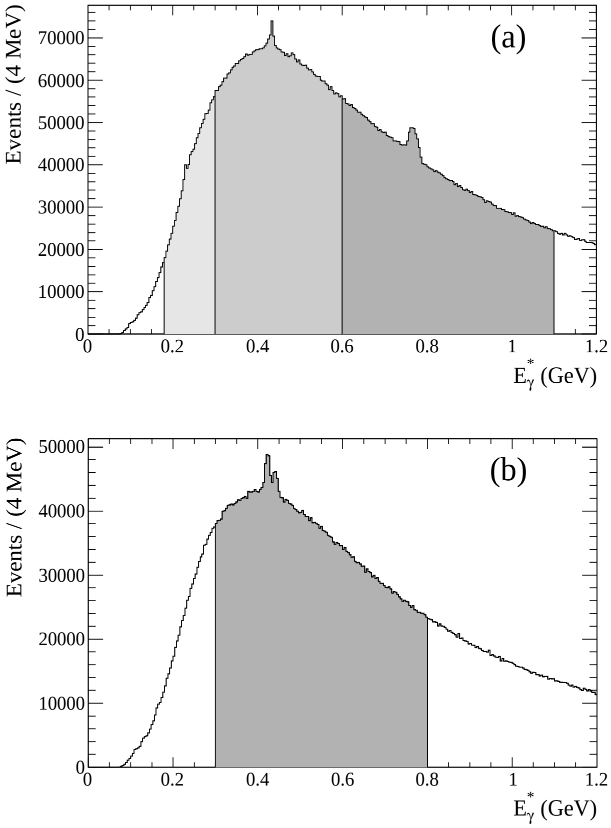

FIG. 3: Raw inclusive converted photon energy spectrum from (a) $\Upsilon(3S)$ and (b) $\Upsilon(2S)$ decays. The shaded areas indicate different regions of interest considered in detail in this analysis.

in the CM frame between the photon momentum and the thrust axis ($|\cos\theta_T|$) [28], and a π^0 veto excluding converted photons producing an invariant mass ($m_{\gamma\gamma}$) consistent with m_{π^0} when paired with any other photon (converted or calorimeter-detected) above a minimum energy ($E_{\gamma 2}$) in the event. A requirement on the ratio of the second and zeroth Fox-Wolfram moments [29] of each event, R_2, is also applied. The reason for using these particular variables is to preferentially select bottomonium decays to hadronic final states and to remove photons from continuum background events and π^0 decays. Table I summarizes the values for the optimized selection criteria.

The efficiency for reconstruction and selection of signal events (ϵ) is determined from MC simulation. A dedicated $e^+e^- \to \mu^+\mu^-\gamma$ sample is used to study our detector model and converted photon efficiency (discussed in Appendix A), and the correspondence between simulation and data is found to be in very good agreement. Once the optimal selection criteria have been applied, $\epsilon \lesssim 1.5\%$ for conversions compared to $\sim 40\%$ for photons in the EMC for the energy range of interest in this analysis. Conversely, a large improvement is gained in photon energy resolution, *e.g.* from $\sim 25\,\mathrm{MeV}$ in the calorimeter to $4\,\mathrm{MeV}$ or better with converted photons. Figure 3 demonstrates both of these features. The sharply-peaking structures correspond to bottomonium transitions, and are narrow and well-resolved in this analysis. Unlike in the photon energy spectrum expected from the EMC [17, 18], the distribution for converted photons drops with energy. The efficiency decreases (also seen in Fig. 2) due to the inability to fully reconstruct the conversion pair as at least one of the individual track momenta approaches the limit of detector sensitivity. We are unable to contribute useful new information on transitions expected below E^*_γ =180 (300) MeV for the $\Upsilon(3S)$ ($\Upsilon(2S)$) analysis, which is why those energy ranges are not considered here.

TABLE I: Acceptance criteria for converted photon events.

Variable	E^*_γ Range (MeV)		
	$\Upsilon(3S)$	$\Upsilon(3S)$	$\Upsilon(2S)$
	$[180, 600]$	$[600, 1100]$	$[300, 800]$
$nTRK$	≥ 8	≥ 8	≥ 8
$\lvert\cos\theta_T\rvert$	< 0.85	< 0.75	< 0.85
$\lvert m_{\gamma\gamma} - m_{\pi^0}\rvert$ (MeV/c^2)	> 10	> 20	> 20
$E_{\gamma 2}$ (MeV)	> 90	> 75	> 70
R_2	< 0.98	< 0.98	< 0.98

The number of signal events for a given bottomonium transition is extracted from the data by performing a χ^2 fit to the E^*_γ distribution in 1 MeV bins. The functional form and parameterization for each photon signal is determined from MC samples, as described below. In general, the lineshape is related to the Crystal Ball function [30], *i.e.* a Gaussian function with a power-law tail. This functional form is used to account for bremsstrahlung losses of the e^+e^- pair. The underlying smooth inclusive photon background is described by a fourth-order polynominal multiplied by an exponential function. This functional form adequately describes the background in each separate energy range.

IV. $\Upsilon(3S)$: $180 \leq E^*_\gamma \leq 300$ MeV

The main purpose of the fit to the $180 \leq E^*_\gamma \leq 300\,\mathrm{MeV}$ region of the $\Upsilon(3S)$ photon energy spectrum, shown in detail in Fig. 4, is to measure the $\chi_{bJ}(2P) \to \gamma\Upsilon(2S)$ transitions. The only previous measurements of these transitions were made by CUSB [9] and CLEO [11] nearly two decades ago. Those analyses examined the low-energy photon spectrum from exclusive $\Upsilon(3S) \to \gamma\gamma\Upsilon(2S)(\ell^+\ell^-)$ decays to derive the branching fractions for $\mathcal{B}(\chi_{b1,2}(2P) \to \gamma\Upsilon(2S))$, and in the case of the CUSB result, to obtain evidence for $\chi_{b0}(2P) \to \gamma\Upsilon(2S)$. We present the first fit to E^*_γ to measure the photon from $\chi_{bJ}(2P) \to \gamma\Upsilon(2S)$ directly. Though this analysis is potentially sensitive to all six $\Upsilon(1D_J) \to \gamma\chi_{bJ}(1P)$ decays, we treat these decays as a small systematic effect to the $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)$ measurement.

The $\chi_{bJ}(2P)$ transition lineshapes are parameterized by a Gaussian with power law tails on both the high and low side. This is best understood as a "double-sided" Crystal Ball function with different transition points and exponents for the high and low tails, but with a common Gaussian mean and standard deviation in the central region. The effects of Doppler broadening, due to the motion of the $\chi_{bJ}(2P)$ in the CM frame, are small ($\sim 2\,\mathrm{MeV}$ width) for these transitions. The $\Upsilon(1D_J)$-related lineshapes are individually parameterized in terms of a single Crystal Ball function. Parameterization of these transitions presents a complication because only the mass of the $J = 2$ state has been measured reliably [31, 32], the value $m_{\Upsilon(1D)} = (10163.7 \pm 1.4)\ \mathrm{MeV}/c^2$ being obtained when the experimental results are averaged. Marginal evidence for the $J = 1$ and 3 states was also seen at $\sim 10152\,\mathrm{MeV}/c^2$ and $\sim 10173\,\mathrm{MeV}/c^2$, respectively [31, 32]. These values are consistent with several theoretical predictions [33], given a shift to bring the theoretical value for $m_{\Upsilon(1D_2)}$ into agreement with experiment. We therefore assume the $m_{\Upsilon(1D_{1,3})}$ mass values stated above to compute the expected energy for transitions from those states. The event yields for these transitions are fixed to the branching fractions expected when $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P))$ [27] is combined with the predictions for $\mathcal{B}(\chi_{bJ}(2P) \rightarrow \gamma\gamma\chi_{bJ}(1P))$ via $\Upsilon(1D_J)$ [34]. The efficiencies for the $\Upsilon(1D)$ transition signals range from approximately 0.17 to 0.30%, monotonically rising with E^*_γ.

Figure 4 shows the measured photon spectrum and results of the fit, before and after subtraction of the inclusive background. In this fit, the parameters describing the background and any systematic offset in the E^*_γ scale are free parameters, together with the signal yields for $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)$ decays. Table II summarizes the fit results. Considering both statistical and systematic uncertainties, we find significant $\chi_{b1,2}(2P) \rightarrow \gamma\Upsilon(2S)$ signals ($> 12\sigma$ and $> 8\sigma$, respectively, where σ represents standard deviation), but do not find evidence for $\chi_{b0}(2P) \rightarrow \gamma\Upsilon(2S)$ decay. The overall energy offset, determined predominantly by the position of the $\chi_{b1,2}(2P)$ transition peaks compared to the nominal [27] values, is found to be inconsequential ($-0.3 \pm 0.2\,\mathrm{MeV}$).

The systematic uncertainties on these measurements (with their approximate sizes given in parentheses below and throughout) include the uncertainty in the fit parameters fixed from MC, uncertainty in the converted photon efficiency, assumptions related to the $\Upsilon(1D_J)$ contributions, uncertainty on masses used to calculate the expected E^*_γ values, the $\Upsilon(mS)$ counting uncertainty, and the effect of the choice for the background shape. For each fit component, all of the parameters fixed to MC-determined values are varied individually by $\pm 1\sigma$ of their uncertainty and the fit repeated. The maximal variation of the fit result for each component is taken as the systematic uncertainty, and summed in quadrature ($\sim 4\%$). The systematic uncertainty on the converted photon efficiency (3.4%) is common to all energy ranges in this analysis, and is estimated using an off-peak control sample, as described in Appendix A. The fits are repeated with the $\Upsilon(1D_J)$ masses individually varied by their approximate experimental uncertainties (± 1.8, ± 1.4, and $\pm 1.5\ \mathrm{MeV}/c^2$ for $J = 1, 2$ and 3, respectively) [32], and the fixed yields by ±50% of the theoretical values [34]. To make a theory-independent determination of the impact due to $\Upsilon(1D_J)$, the fit is also repeated with four of the $\Upsilon(1D_J) \rightarrow \gamma\chi_{bJ}(1P)$ yields free to vary (the $\Upsilon(1D_1) \rightarrow \gamma\chi_{b1}(1P)$ and $\Upsilon(1D_3) \rightarrow \gamma\chi_{b2}(1P)$ yields are fit as a single component because their E^*_γ values are nearly identical, and the $\Upsilon(1D_1) \rightarrow \gamma\chi_{b2}(1P)$ transition is overwhelmed by the main $\chi_{b1,2}(2P) \rightarrow \gamma\Upsilon(2S)$ peaks and remains fixed). Under this scenario, none of the $\Upsilon(1D_J)$-related transitions is found to be significant, and the yields are consistent with the theoretical predictions within statistical uncertainty. The $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)$ yields are not significantly affected. The change in the fit yields for all of these alternative cases are added in quadrature and taken as the systematic uncertainty due to $\Upsilon(1D_J)$ decays ($\sim 2\%$). It is worth reiterating that the excellent resolution obtained by using converted photons separates the $\Upsilon(1D_J)$- and $\chi_{bJ}(2P)$-related components in E^*_γ, which is why the impact of the $\Upsilon(1D_J)$ states does not dominate the measurement uncertainty. The fit is repeated with the bottomonium masses (hence, E^*_γ values) varied according to the PDG uncertainties [27], and the change in the yield added in quadrature ($\sim 2\%$). The number of $\Upsilon(mS)$ mesons and its uncertainty (1.0%) were calculated separately, based on visible cross sections computed from dedicated $e^+e^- \rightarrow e^+e^-(\gamma)$ and $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ control samples. Finally, the background shape was replaced by a fifth-order polynomial and half of the resulting change in the yield ($< 1\%$) taken as the symmetric error due to this assumed parameterization.

We find $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)) \times \mathcal{B}(\chi_{bJ} \rightarrow \gamma\Upsilon(2S)) = (-0.3 \pm 0.2^{+0.4}_{-0.5})\%$, $(2.5 \pm 0.1 \pm 0.1)\%$, and $(1.1 \pm 0.1 \pm 0.1)\%$ for $J = 0$, 1, and 2, respectively. Using $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P))$ from [27], we derive $\mathcal{B}(\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)) = (-4.9 \pm 2.9^{+0.7}_{-0.8} \pm 0.5)\%$, $(19.5 \pm 1.1^{+1.1}_{-1.0} \pm 1.9)\%$, and $(8.6^{+0.9}_{-0.8} \pm 0.5 \pm 1.1)\%$, where the errors are statistical, systematic, and from the uncertainty on $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P))$, respectively. From these values, we calculate a 90% confidence level upper limit of $\mathcal{B}(\chi_{b0}(2P) \rightarrow \gamma\Upsilon(2S)) < 2.9\%$ [35]. Past experimental results [9, 11] averaged by the PDG [27] rely on assumptions for the branching fractions of $\Upsilon(2S) \rightarrow \ell^+\ell^-$ and $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$ and their uncertainties that are no longer valid. In Table II, we have rescaled these previous results using the current values in order to make a useful comparison. We find our results to be in good agreement with the previous results, and to be the most precise values to date for the $J = 1$ and 2 decays.

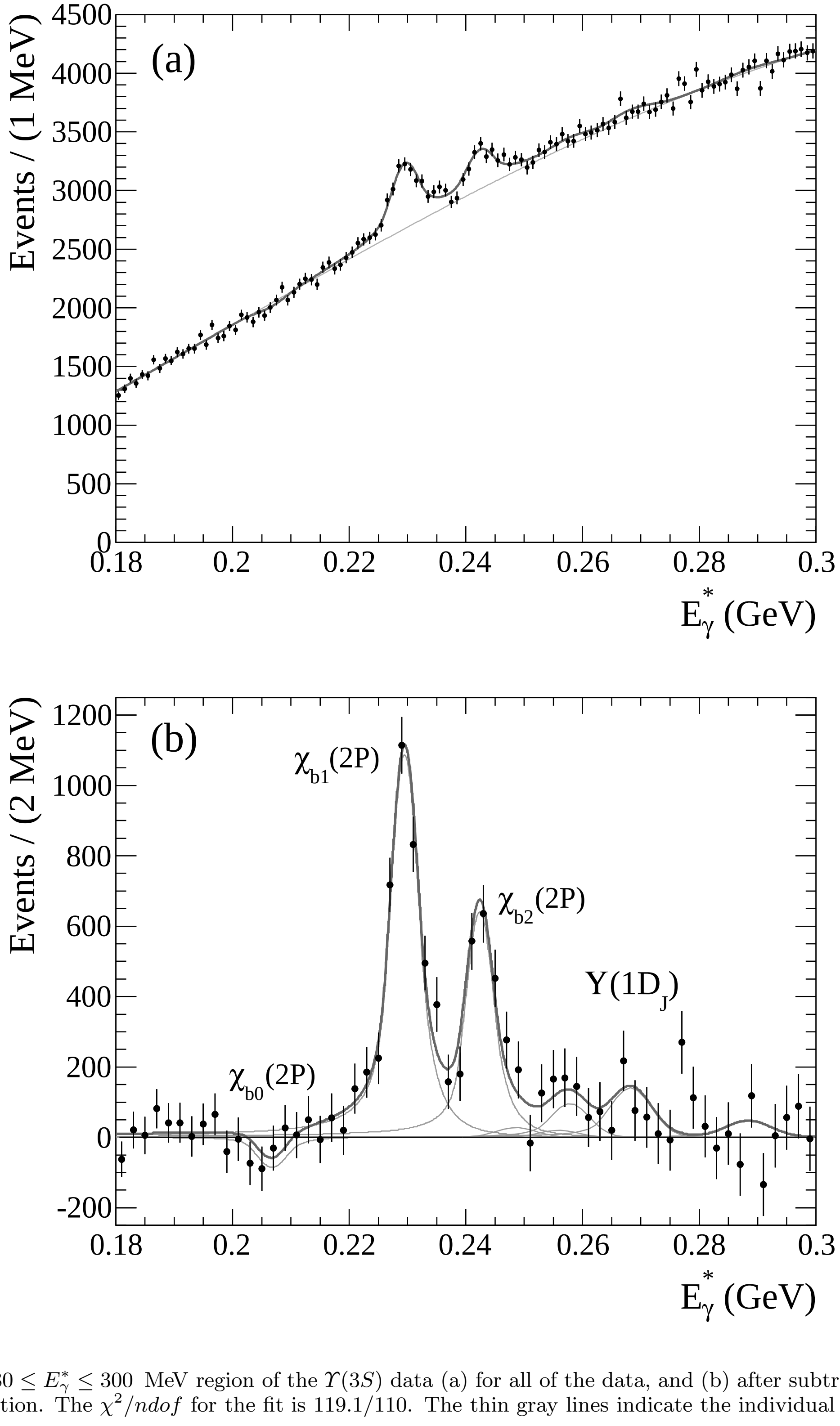

FIG. 4: Fit to the $180 \le E_\gamma^* \le 300$ MeV region of the $\Upsilon(3S)$ data (a) for all of the data, and (b) after subtraction of the fitted background contribution. The $\chi^2/ndof$ for the fit is 119.1/110. The thin gray lines indicate the individual signal components in the fit, as labelled.

TABLE II: Summary of the analysis of the $180 \leq E^*_\gamma \leq 300$ MeV region of the $\Upsilon(3S)$ data. The E^*_γ column lists the transition energy assumed in this analysis. Errors on the yield are statistical only. Regarding the derived $\mathcal{B}(\chi_{bJ}(2P) \to \gamma\Upsilon(2S))$: the *BABAR* value is from this paper, while the CUSB and CLEO columns are derivations based on [9] and [11] using up-to-date secondary branching fractions from [27]. For the *BABAR* result, the listed uncertainties are statistical, systematic, and from the uncertainties on secondary branching fractions, respectively. For the other results, the total uncertainty (all sources combined in quadrature) is given. Upper limits are given at the 90% confidence level.

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) *BABAR*	CUSB	CLEO
$\chi_{b0}(2P) \to \gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.9 \pm 2.9^{+0.7}_{-0.8} \pm 0.5$ (< 2.9)	3.6 ± 1.6	< 5.2
$\chi_{b1}(2P) \to \gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$19.5 \pm 1.1^{+1.1}_{-1.0} \pm 1.9$	13.6 ± 2.4	21.1 ± 4.5
$\chi_{b2}(2P) \to \gamma\Upsilon(2S)$	242.3	2462 ± 243	0.190	$8.6^{+0.9}_{-0.8} \pm 0.5 \pm 1.1$	10.9 ± 2.2	9.9 ± 2.7

V. $\boldsymbol{\Upsilon(3S) : 300 \leq E^*_\gamma \leq 600}$ MeV

The $300 \leq E^*_\gamma \leq 600$ MeV range in the inclusive $\Upsilon(3S)$ photon energy spectrum, shown in Fig. 5, is complicated by many radiative bottomonium transitions. A principal feature is the photon lines from the three direct $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ decays. Photons from the secondary decays, $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$, have energies that overlap with these initial transitions. There are several ways to produce $\chi_{bJ}(1P)$ from $\Upsilon(3S)$, each with unique Doppler broadening and relative rate. These decays "feed-down" to produce many extraneous $\chi_{bJ}(1P)$ mesons that contribute substantially to the background level through subsequent $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ decay. At the lower edge of this energy range, there are potential contributions from $\Upsilon(3S) \to \gamma\eta_b(2S)$ and $\Upsilon(2S)$ production from initial state radiation (ISR).

The best known of the $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ branching fractions comes from the CLEO experiment, which was able to isolate the $\Upsilon(3S) \to \gamma\chi_{b0}(1P)$ signal [13]. A separate analysis of $\chi_{bJ}(1P)$ decays to multihadronic final states further set upper limits on $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(1P))$ [36]. A recent analysis of $\Upsilon(3S) \to \gamma\chi_{b1,2}(1P) \to \gamma\gamma\Upsilon(1S)$ transitions with exclusive $\Upsilon(1S) \to \ell^+\ell^-$ decays has resulted in a measurement of $\Upsilon(3S) \to \gamma\chi_{b1,2}(1P)$ branching fractions [14]. Our improved E^*_γ resolution with the converted photon sample allows us to disentangle the overlapping photon lines to make a direct measurement of these radiative transitions as well. We also search for a signal for $\Upsilon(3S) \to \gamma\eta_b(2S)$.

The direct $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ lineshapes are parameterized using the "double-sided" Crystal Ball function described in Sec. IV plus an independent Gaussian to account for broadening from non-linearities in the E^*_γ resolution due to low momentum tracks encountered in this energy range. The $\Upsilon(3S) \to \gamma\eta_b(2S)$ lineshape is modeled with the convolution of a relativistic Breit-Wigner function (natural lineshape for the $\eta_b(2S)$) and a Crystal Ball function (experimental resolution function), where the Breit-Wigner function has been modified by a transformation of variables to E^*_γ using Eq. (1). The ISR-produced $\Upsilon(2S)$ signal is parameterized with a Crystal Ball function, for which the width is dominated by the spread in the e^+e^- beam energy.

The lineshapes for the decays $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ depend on the initial decays that produced the $\chi_{bJ}(1P)$ states. We consider six main production pathways:

- $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\gamma\Upsilon(2S) \to \gamma\gamma\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\gamma\Upsilon(1D_J) \to \gamma\gamma\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \pi\pi\Upsilon(2S) \to \pi\pi\gamma\chi_{bJ}(1P)$
- $\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \gamma\pi\pi\chi_{bJ}(1P)$
- $e^+e^- \to \gamma_{ISR}\Upsilon(2S) \to \gamma_{ISR}\gamma\chi_{bJ}(1P)$.

The feed-down contribution from $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ is determined directly from the fit to the data. The lineshapes for the subsequent $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ decays are distorted by Doppler-broadening effects. We parameterize the $\chi_{bJ}(1P)$ transition lineshape with the convolution of a rectangular function and a Crystal Ball function. Because of the large Doppler width (~ 20 MeV), the resulting shape is relatively broad and non-peaking. In the fit, the relative yields of the direct to the secondary transitions are fixed according to the ratios of the expected efficiencies for each mode, and the branching fractions for the $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ decays (to be discussed below).

There are two 3γ pathways from $\Upsilon(3S)$ to $\chi_{bJ}(1P)$. Decays via $\Upsilon(2S)$ are fairly well understood, and the precision branching fraction results from Sec. IV are used to determine the expected yields and uncertainties. In contrast, the decays via $\Upsilon(1D_J)$ have not been measured in detail. We rely on theoretical predictions [34], found to be consistent with an experimental measurement of the 4γ cascade to $\Upsilon(1S)$ [31], to estimate the total feed-down component. We take the uncertainties on $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P))$ [27] and introduce a 30% uncertainty on each theoretically calculated branching fraction in the decay chain. Doppler effects introduce a smooth ~ 5 MeV broadening in these (and other) multi-step decay processes, thus the lineshapes for the individual 3γ pathways are adequately parameterized using a standard Crystal Ball function.

There are two di-pion decay chains leading to $\chi_{bJ}(1P)$: either via $\Upsilon(3S) \to \pi\pi\Upsilon(2S)$ or $\chi_{bJ}(2P) \to \pi\pi\chi_{bJ}(1P)$.

TABLE III: Summary of the analysis of the $300 \leq E^*_\gamma \leq 600\,\mathrm{MeV}$ region of the $\Upsilon(3S)$ data. The E^*_γ column lists the transition energy assumed in this analysis. Errors on the yield are statistical only. For the Derived Branching Fraction, the *BABAR* values are from this work, and the CLEO results are from [13, 14]. The upper limit is given at the 90% confidence level.

Transition	E^*_γ	Yield	ϵ	Derived Branching Fraction $(\times 10^{-3})$	
	(MeV)		(%)	*BABAR*	CLEO
$\Upsilon(3S) \to \gamma\chi_{b2}(1P)$	433.1	9699 ± 318	0.794	$10.6 \pm 0.3 \pm 0.6$	7.7 ± 1.3
$\Upsilon(3S) \to \gamma\chi_{b1}(1P)$	452.2	483 ± 315	0.818	$0.5 \pm 0.3^{+0.2}_{-0.1}$ (< 1.1)	1.6 ± 0.5
$\Upsilon(3S) \to \gamma\chi_{b0}(1P)$	483.5	2273 ± 307	0.730	$2.7 \pm 0.4 \pm 0.2$	3.0 ± 1.1

The former has been precisely measured by *BABAR* in a recent analysis of the recoil against $\pi^+\pi^-$ to search for the $h_b(1P)$ state [37]. We combine the branching fraction from that analysis with the PDG average [27] to obtain $\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S) = (2.7 \pm 0.2)\%$. For the $\pi^0\pi^0$ transition, we use the current world average branching fraction value [27]. The relevant MC samples are generated with the experimentally-determined $m_{\pi^+\pi^-}$ distribution [38]. Di-pion transitions between $\chi_{bJ}(2P)$ and $\chi_{bJ}(1P)$ for J =1 and 2 have been measured experimentally by CLEO [39]. The above-mentioned *BABAR* di-pion analysis [37] also measured these quantities, which are averaged with the CLEO results to derive $\mathcal{B}(\chi_{bJ}(2P) \to \pi^+\pi^-\chi_{bJ}(1P))$ equal to $(9.1 \pm 1.0) \times 10^{-3}$ and $(5.0 \pm 0.6) \times 10^{-3}$ for $J = 1$ and 2, respectively. Decays to the $J = 0$ state, with different initial and final J values, and via $\pi^0\pi^0$ have thus far been below the level of experimental sensitivity. To calculate the expected feed-down, we assume isospin conservation such that $\Gamma_{\pi^0\pi^0} = \frac{1}{2}\Gamma_{\pi^+\pi^-}$, and estimate $\mathcal{B}(\chi_{b0}(2P) \to \pi\pi\chi_{b0}(1P))$ to be about one-fifth of that of the other J states [40]. We assume a 30% uncertainty on all theoretically-estimated branching fractions.

Radiative decay of ISR-produced $\Upsilon(2S)$ mesons can yield $\chi_{bJ}(1P)$ signals. The estimated production cross section for $\Upsilon(2S)$ is (28.6 ± 1.4) pb [41], where we have assigned a 5% uncertainty to this theoretical calculation. We combine this with the $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$ branching fraction [27] to determine the size of this contribution to the background. From MC simulation, we conclude that the lineshape may be parameterized with a Crystal Ball function.

Except for feed-down from $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$, which is determined from the data, the yields of these components are fixed in the fit. The branching fractions for the final step of the decay chain, $\mathcal{B}(\chi_{bJ}(1P) \to \gamma\Upsilon(1S))$, are measured precisely for $J = 1$ and 2 in Sec. VI. Our values for these decays are averaged with results from CLEO [14]. For decays with $J = 0$, both the CLEO [14] and Belle [42] Collaborations have recently presented observations. Since we do not observe this decay in Sec. VI, we use the measured branching fraction value from CLEO [14].

In the fit, we include two components related to $h_b(1P) \to \gamma\eta_b(1S)$ decays. The $h_b(1P)$ decay is assumed to decay with a large branching fraction via $h_b(1P) \to \gamma\eta_b(1S)$ [43]. The two relevant $h_b(1P)$ production mechanisms are $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ and $\Upsilon(3S) \to \pi^0 h_b(1P)$. *BABAR* has studied both of these modes, finding $\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) < 2.5 \times 10^{-4}$ [37] and $\mathcal{B}(\Upsilon(3S) \to \pi^0 h_b(1P)) \times \mathcal{B}(h_b(1P) \to \gamma\eta_b(1S)) = (4.7 \pm 1.5 \pm 0.6) \times 10^{-4}$ [44]. Due to the effects of Doppler broadening, we parameterize the decay via π^0 using the Doppler-broadened Crystal Ball function as described for $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ transitions from $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$, and via $\pi^+\pi^-$ using a standard Crystal Ball. The yields for these components are fixed in the fit, and are nearly negligible.

In the fit, all of the lineshape parameters are fixed to the MC-determined values except for the yield of the $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ (and its related $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ components), an overall E^*_γ scale offset, and the background lineshape parameters. The feed-down yields are fixed using the branching fractions as described above. Repeated trials of the signal extraction on simulated datasets determine that, given the low efficiency and expected number of events, and high level of background, obtaining a reliable yield for $\eta_b(2S)$ and ISR-produced $\Upsilon(2S)$ is not possible. These components are therefore not included in the fit. The measured photon energy spectrum and the fitted yields are presented in Fig. 5, before and after the subtraction of the inclusive background. There is a clear separation of the $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ transitions, enabling us to observe the transitions to $J = 0, 2$, and find only a very small indication for $J = 1$. Table III summarizes the fit results.

We consider systematic uncertainties due to the choice of background shape $(1-2\%)$, the effect of fixing parameters to the MC-determined values $(3-6\%)$, uncertainty in the photon conversion efficiency (3.4%), uncertainty in the $\Upsilon(mS)$ counting (1.0%), uncertainty in the bottomonium masses $(1-3\%)$, and the impact of fixed feed-down yields (2%). The values in parentheses are representative of the $\Upsilon(3S) \to \gamma\chi_{b0,2}(1P)$ decays; for the χ_{b1}-related results, the effects of the feed-down lineshapes and the yields and the background shape dominate (about 20% each) due the marginal signal size. The evaluation of these uncertainties is done as described in Sec. IV, with the exception of the feed-down-related uncertainty that is unique to this energy region. To assess the uncertainty related to the assumed branching fractions, we repeat the analysis many times with the value of each input branching fraction varied randomly within its total uncertainty. We adopt the standard deviation of the change in the

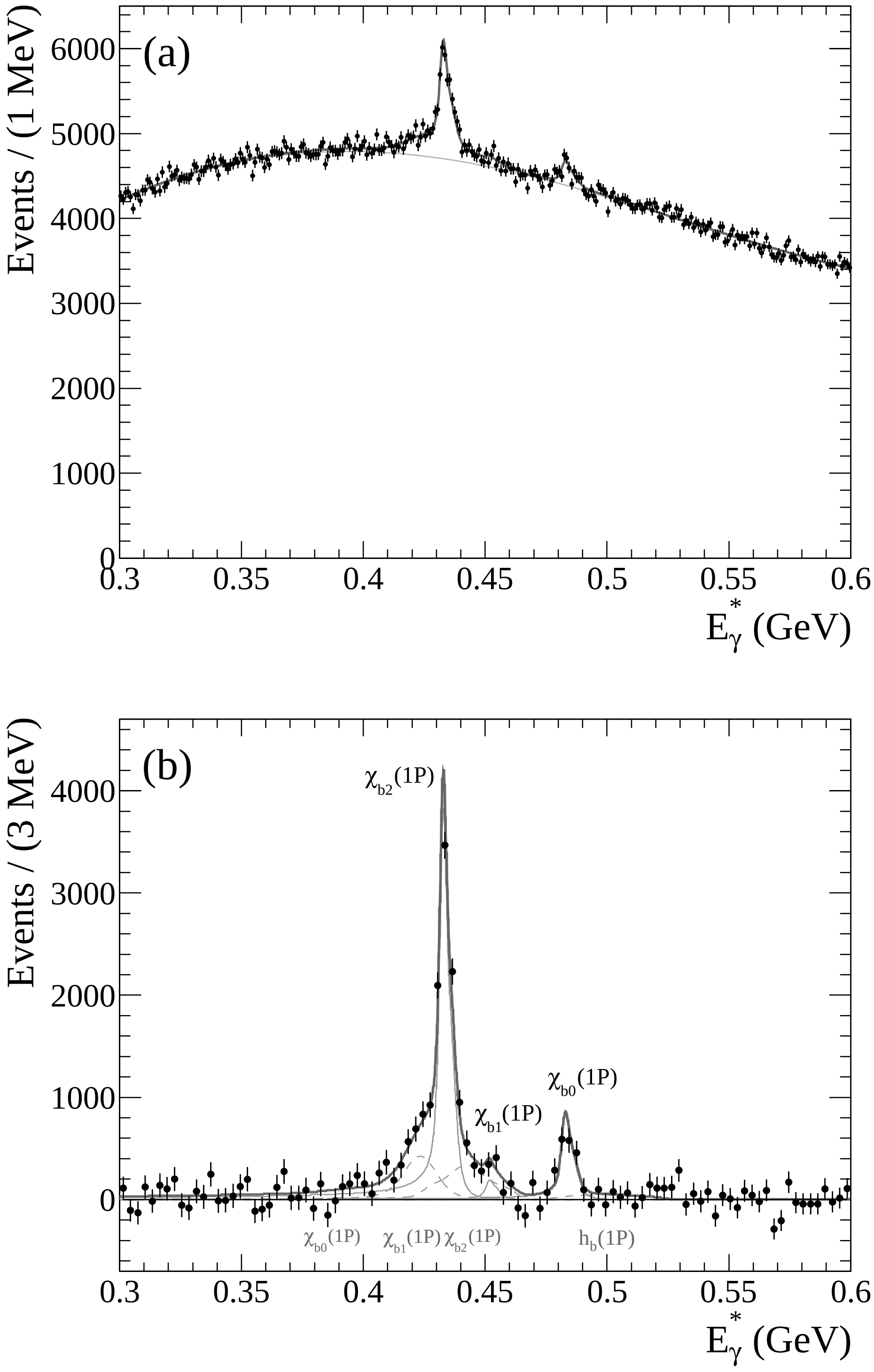

FIG. 5: Fit to the $300 \leq E^*_\gamma \leq 600$ MeV region of the $\Upsilon(3S)$ data (a) for all of the data, and (b) after subtraction of the fitted background contribution. The $\chi^2/ndof$ for the fit is 316/291. The thick solid lines indicate the total fit, the thin solid lines indicate the $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ components, and the dashed lines indicate those from $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ and $h_b(1P) \to \gamma\eta_b(1S)$, as labeled.

results as a systematic error. As a cross-check, we repeat the fit with the yields of the $\Upsilon(1D)$-related feed-down components allowed to vary as a free parameter. We find only a small change ($< 2\%$) in the overall branching fraction results, and consider this to be sufficiently accounted for by the systematic uncertainty determined from our procedure of varying the branching fractions. Including ISR and $\eta_b(2S)$ components in the fit produces an effect of less than $\sim 1\%$, due to their slight impact on determining the overall background shape.

We measure $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(1P)) = (2.7\pm0.4\pm0.2)\times 10^{-3}$, $(0.5\pm0.3^{+0.2}_{-0.1})\times10^{-3}$, and $(10.6\pm0.3\pm0.6)\times10^{-3}$ for $J = 0, 1$ and 2, respectively. We observe evidence for the $\Upsilon(3S) \to \gamma\chi_{b0,2}(1P)$ transitions, with total significances greater than 6.8σ and 16σ, respectively. We do not find evidence for the suppressed $\Upsilon(3S) \to \gamma\chi_{b1}(1P)$ decay, and set the 90% confidence level upper limit of $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b1}(1P)) < 1.1 \times 10^{-3}$. These results are consistent with previous limits [36], and improve upon the only measured value for the $J = 0$ transition [13]. Our measurements of the $\Upsilon(3S) \to \gamma\chi_{b1,2}(1P)$ branching fractions both differ from the recent CLEO observations [14] by nearly 2σ. Forcing the $\chi_{b1,2}(1P)$ yields in our fit to match the CLEO results gives a poor $\chi^2/ndof$ of 399/293. However, using the $\mathcal{B}(\chi_{b1,2}(1P) \to \gamma\Upsilon(1S))$ results from Sec. VI to derive a total $\Upsilon(3S) \to \gamma\gamma\Upsilon(1S)$ branching fraction via $\chi_{b1,2}(1P)$ (comparable to "J =1 and 2" [14]), we find the results of the two experiments to be in close agreement.

Adopting these results, we search for the $\Upsilon(3S) \to \gamma\eta_b(2S)$ transition in the range $335 \leq E^*_\gamma \leq 375\,\text{MeV}$ and find no evidence. Taking into account the dominant statistical uncertainty, we derive an upper limit of $\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b(2S)) < 1.9\times10^{-3}$ at the 90% confidence level. This limit is a factor of two larger than the limit set by CLEO [13].

VI. $\Upsilon(2S)$: $300 \leq E^*_\gamma \leq 800$ MeV

We study five possible signals in the $300 \leq E^*_\gamma \leq 800$ MeV range in $\Upsilon(2S)$ data: three $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ transitions, ISR $\Upsilon(1S)$ production, and $\Upsilon(2S) \to \gamma\eta_b(1S)$. This energy region, shown in Fig. 6, has been analysed using calorimeter-detected photons by both *BABAR* [18] and CLEO [19], the former finding evidence to confirm the $\eta_b(1S)$. The improvement in resolution from the converted photon sample could allow a precise measurement of the $\eta_b(1S)$ mass. However, because E^*_γ for the $\Upsilon(2S) \to \gamma\eta_b(1S)$ transition is $\approx 613\,\text{MeV}$ (compared to $\approx 920\,\text{MeV}$ in the $\Upsilon(3S)$ data), its measurement is more difficult due to a lower detection efficiency and larger inclusive photon background. Studying this energy range is nonetheless useful, since the branching fractions for $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ have had large uncertainties [3, 5, 6] until very recently [14], and the values are necessary inputs to the analysis described in Sec. V. The $J = 0$ decay has also only been recently observed [14, 42]. These external measurements were unavailable when this analysis was initiated.

We parameterize the $\chi_{bJ}(1P)$ transition lineshape with a Doppler-broadened Crystal Ball function, as described in Sec. V. The ISR and $\Upsilon(2S) \to \gamma\eta_b(1S)$ lineshapes are modeled with a Crystal Ball function and a relativistic Breit-Wigner convolved with a Crystal Ball, respectively. The lineshape parameters are determined from MC samples. Several different natural widths are tested for the $\eta_b(1S)$, and because the Crystal Ball parameter values (related to E^*_γ resolution) are found to be independent of the width, the values averaged over all samples are used. In the fit to the data, all of the parameters are fixed to these MC-determined values, except for the yields for the $\chi_{bJ}(1P)$, ISR, and $\eta_b(1S)$ signals, the mass of the $\eta_b(1S)$, the inclusive background shape parameters, and an overall E^*_γ scale offset. The width of $\eta_b(1S)$ is fixed to 10 MeV.

Figure 6 shows the converted photon energy spectrum before and after the subtraction of the inclusive background, with an inset focusing on the region of the expected $\Upsilon(2S) \to \gamma\eta_b(1S)$ transition. The E^*_γ resolution provides clear separation of the $\chi_{b1,2}(1P)$-related peaks, allowing for the first direct measurement of these transitions in an inclusive sample. The results of the fit are summarized in Table IV. We find no evidence for $\chi_{b0}(1P) \to \gamma\Upsilon(1S)$ decay. The $\Upsilon(1S)$ yield from ISR production is consistent, within large uncertainties, with the result scaled from the previous *BABAR* measurement [18]. As expected from signal extraction studies on simulated datasets, the search for a signal in the $\Upsilon(2S) \to \gamma\eta_b(1S)$ energy region does not find a reliable result. Estimating the statistical significance from the change in χ^2 of the fit with and without this component results in the equivalent of a less than 2.5σ effect. The E^*_γ scale offset in this energy range is $-0.9^{+0.5}_{-0.4}\,\text{MeV}$.

The systematic uncertainties on these measurements are related to the choice of background shape, the effect of fixing parameters to the MC-determined values, uncertainty in the photon conversion efficiency, uncertainty in the $\Upsilon(mS)$ counting, uncertainties in the bottomonium masses, and assumptions on the $\eta_b(1S)$ width. The methodology for the evaluation of these uncertainties has been described for the most part in Sec. IV. The systematic uncertainty related to the $\eta_b(1S)$ width is estimated by finding the maximal change in yield when the fit is repeated using a range of widths between $2.5 - 15\,\text{MeV}$, values consistent with a wide range of theoretical predictions. For the $\chi_{b1,2}(1P) \to \gamma\Upsilon(1S)$ transitions, the largest sources of uncertainty are related to the fixed lineshape parameters ($3 - 4\%$), uncertainty in the bottomonium masses ($\sim 4\%$ for $\chi_{b2}(2P)$, and dominant for the E^*_γ scale uncertainty) and the conversion efficiency (3.3%). Each of the remaining sources contributes 1% or less. For the $\eta_b(1S)$ signal, systematic uncertainties dominate the result. The largest effects are due to varying the background shape ($\sim 31\%$), the bottomonium masses ($\sim 25\%$), the MC-determined parameters ($\sim 22\%$), and

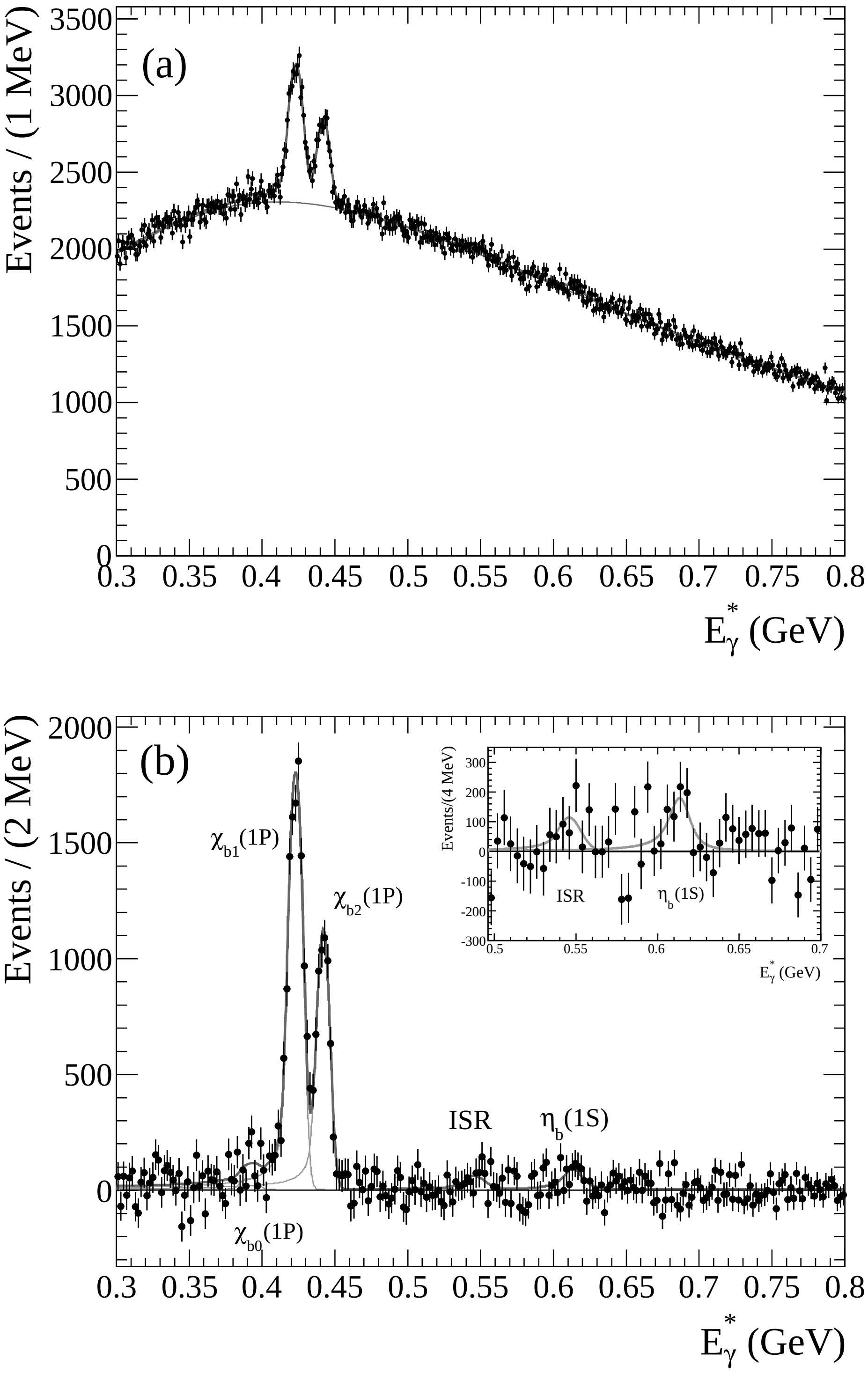

FIG. 6: Fit to the $300 \le E^*_\gamma \le 800$ MeV region of the $\Upsilon(2S)$ data (a) for all of the data, and (b) after subtraction of the fitted background contribution, where the inset focuses on the $\Upsilon(2S) \to \gamma\eta_b(1S)$ region of the fit. The thin lines indicate the individual fit components. For this fit, $\chi^2/ndof = 511.0/487$.

TABLE IV: Summary of the analysis of the $300 \leq E_\gamma^* \leq 800$ MeV region of the $\Upsilon(2S)$ data. The E_γ^* column lists the transition energy assumed in this analysis, or in the case of $\Upsilon(2S) \to \gamma\eta_b(1S)$, the most significant ($\sim 1.7\sigma$) feature in the relevant E_γ^* region. Errors on the yield are statistical only. Regarding the derived branching fractions, the *BABAR* value is from this paper, while the Crystal Ball (CB) and CUSB columns are derivations based on Ref. [3] and [5] using up-to-date secondary branching fractions from the PDG [27]; the CLEO results are from [14]. For the *BABAR* result, the listed uncertainties are statistical, systematic, and from the uncertainties on secondary branching fractions, respectively. Upper limits are given at the 90% confidence level. Dashes indicate that no value has been reported in the relevant reference.

Transition	E_γ^*	Yield	ϵ	Derived Branching Fraction (%)			
	(MeV)		(%)	*BABAR*	CB	CUSB	CLEO
$\chi_{b0}(1P) \to \gamma\Upsilon(1S)$	391.5	391 ± 267	0.496	$2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2$ (< 4.6)	< 5	< 12	1.7 ± 0.4
$\chi_{b1}(1P) \to \gamma\Upsilon(1S)$	423.0	12604 ± 285	0.548	$36.2 \pm 0.8 \pm 1.7 \pm 2.1$	34 ± 7	40 ± 10	33.0 ± 2.6
$\chi_{b2}(1P) \to \gamma\Upsilon(1S)$	442.0	7665^{+270}_{-272}	0.576	$20.2 \pm 0.7^{+1.0}_{-1.4} \pm 1.0$	25 ± 6	19 ± 8	18.5 ± 1.4
$\Upsilon(2S) \to \gamma\eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	1109 ± 348	1.050	$0.11 \pm 0.04^{+0.07}_{-0.05}$ (< 0.22)	-	-	-

the $\eta_b(1S)$ width ($\sim 16\%$).

We measure $\mathcal{B}(\Upsilon(2S) \to \gamma\chi_{bJ}(1P)) \times \mathcal{B}(\chi_{bJ}(1P) \to \gamma\Upsilon(1S)) = (8.6 \pm 5.9^{+3.8}_{-2.7}) \times 10^{-4}$, $(25.0 \pm 0.6^{+1.2}_{-1.1}) \times 10^{-3}$, and $(14.5 \pm 0.5^{+0.7}_{-1.0}) \times 10^{-3}$, for $J = 0$, 1 and 2, respectively. Using $\mathcal{B}(\Upsilon(2S) \to \gamma\chi_{bJ}(1P))$ from the PDG [27], we derive $\mathcal{B}(\chi_{bJ}(1P) \to \gamma\Upsilon(1S)) = (2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2)\%$, $(36.2 \pm 0.8 \pm 1.7 \pm 2.1)\%$, and $(20.2 \pm 0.7^{+1.0}_{-1.4} \pm 1.0)\%$, where the uncertainties are statistical, systematic, and from the uncertainty on $\mathcal{B}(\Upsilon(2S) \to \gamma\chi_{bJ}(1P))$, respectively. We calculate a 90% confidence level upper limit of $\mathcal{B}(\chi_{b0}(1P) \to \gamma\Upsilon(1S)) < 4.6\%$. As previously, we rescale the existing results [3, 5] using the most up-to-date secondary branching fraction values [27] to obtain the results quoted in Table IV. Our $\chi_{bJ}(1P)$ transition results agree with the previous measurements, but represent a two- to three-fold reduction in the total uncertainty. We find reasonable agreement with, and a comparable precision to, the recent measurements from CLEO [14]. When the yield-related systematic uncertainties on the measurement of the $\eta_b(1S)$ candidate are taken into account, the result is further reduced in significance to an equivalent of $\sim 1.7\sigma$. We find no evidence for an $\eta_b(1S)$ signal in this analysis of the $\Upsilon(2S)$ dataset, and set a corresponding limit of $\mathcal{B}(\Upsilon(2S) \to \gamma\eta_b(1S)) < 0.22\%$.

VII. $\Upsilon(3S)$: $600 \leq E_\gamma^* \leq 1100$ MeV

The analysis of the $600 \leq E_\gamma^* \leq 1100$ MeV region for the $\Upsilon(3S)$, shown in Fig. 7, is very similar to that in Sec. VI of the $300 \leq E_\gamma^* \leq 800$ MeV region for the $\Upsilon(2S)$. Again, we study potential signals from three $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ transitions, $\Upsilon(1S)$ production from ISR, and $\Upsilon(3S) \to \gamma\eta_b(1S)$. In this case, the calorimeter-based analysis of the same region produced the discovery of the $\eta_b(1S)$ [17]. The higher E_γ^* value for $\Upsilon(3S) \to \gamma\eta_b(1S)$ offers the advantages of both an increased efficiency and lower background level compared to the analagous analysis in $\Upsilon(2S)$ data, and therefore a better sensitivity for the observation of $\eta_b(1S)$. There is also the possibility of updating the measurements of $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ transitions, including confirmation of the decay of the $J = 0$ state [9, 11].

We parameterize the signal lineshape in the same manner as described in Sec. VI, with Doppler-broadened Crystal Ball functions for the $\chi_{bJ}(2P)$ transitions, a Crystal Ball for ISR production of the $\Upsilon(1S)$, and the relativistic Breit-Wigner Crystal Ball convolution for the $\eta_b(1S)$ signal. As before, all of the lineshape parameters are fixed to their MC-determined values, with the yields for the $\chi_{bJ}(2P)$, ISR, and $\eta_b(1S)$ signals, the mass of the $\eta_b(1S)$, the inclusive background shape parameters, and an overall E_γ^* scale offset free to vary in the fit. An $\eta_b(1S)$ width of 10 MeV is assumed.

Figure 7 shows the converted photon energy spectrum and fitted yields before and after the subtraction of the inclusive background, with an inset focusing on the E_γ^* region of the expected $\Upsilon(3S) \to \gamma\eta_b(1S)$ transition. The results are summarized in Table V. Although the $\chi_{b1,2}(1P)$-related peaks overlap, the E_γ^* resolution is still sufficient to measure the separate contributions. We find no evidence for $\chi_{b0}(2P) \to \gamma\Upsilon(1S)$ decay. The $\Upsilon(1S)$ yield from ISR production is in greement with the expectation from the previous *BABAR* measurement [17]. The best fit for a signal in the E_γ^* range corresponding to $\Upsilon(3S) \to \gamma\eta_b(1S)$ has $E_\gamma^* \approx 908$ MeV, which is a departure from, but not significantly inconsistent with, the nominal PDG value of $920.6^{+2.8}_{-3.2}$ [27]. Estimating the statistical significance from the change in χ^2 of the fit with and without this component results in the equivalent of a less than 2.9σ effect. Based predominantly on the positions of the $\chi_{b1,2}(2P)$ transition peaks, the E_γ^* scale offset in this energy range is $-0.9^{+0.4}_{-0.9}$ MeV. We further verify that the E_γ^* scale is correct by repeating the fit with the peak positions of the $\chi_{bJ}(2P)$ and ISR components allowed to vary, and they are found at the expected locations. We also repeat the analysis with the E_γ^* scale offset forced to reproduce an $\eta_b(1S)$ result corresponding to the E_γ^* value for the nominal $m_{\eta_b(1S)}$. The assumption that the observed mass difference is due to an offset in the energy scale by ~ 12 MeV is completely inconsistent with the photon energies observed for the well-established $\chi_{b1,2}(2P)$ states. Even with only a 5 MeV shift, the fit returns $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ yields that disagree with the

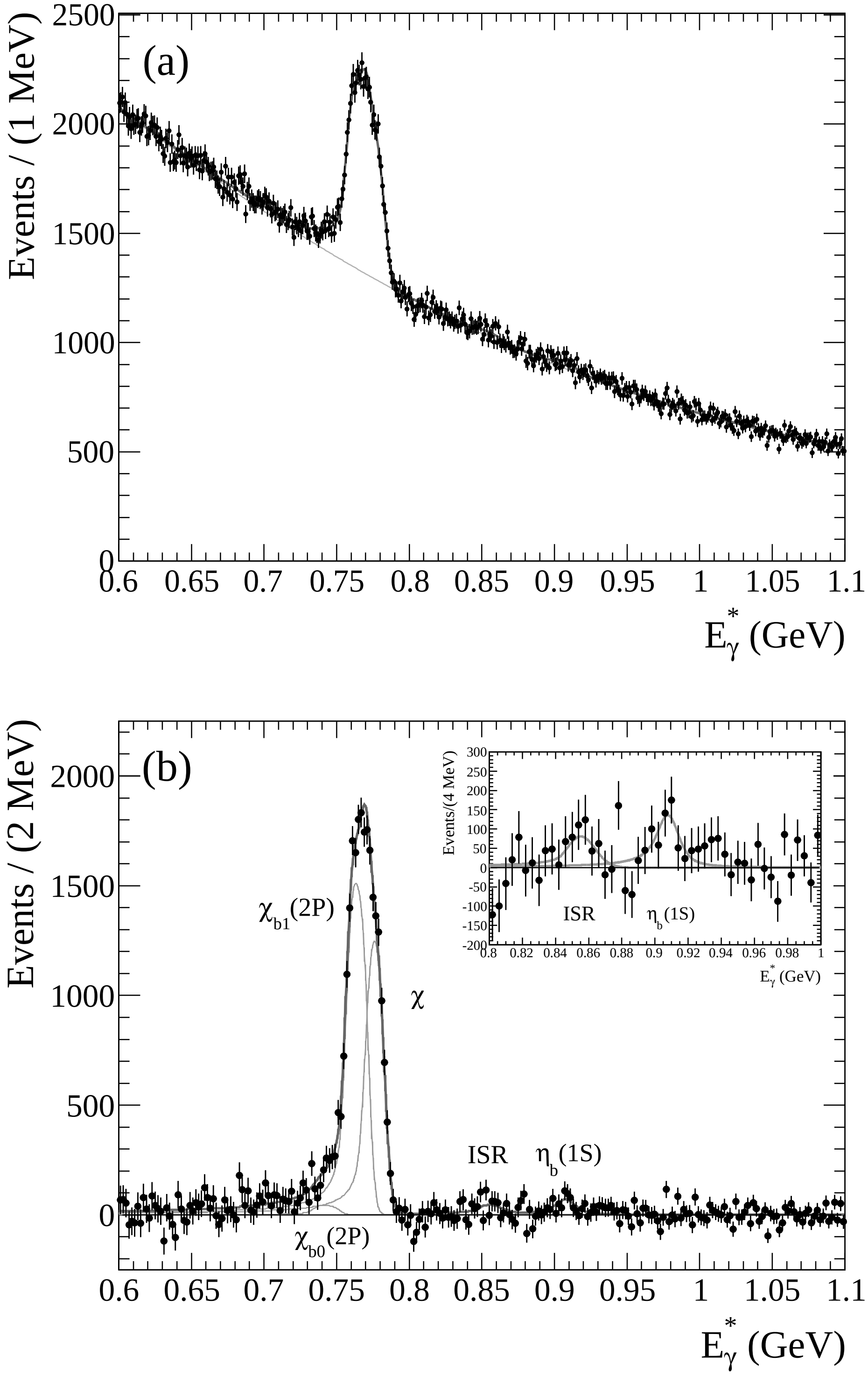

FIG. 7: Fit to the $600 \leq E^*_\gamma \leq 1100$ MeV region of the $\Upsilon(3S)$ data (a) for all of the data, and (b) after subtraction of the fitted background contribution, where the inset focuses on the $\Upsilon(3S) \to \gamma\eta_b(1S)$ region of the fit. The thin lines indicate the individual fit components. For this fit, $\chi^2/ndof = 442.9/487$.

world average [27] by more than a factor of two, and a $\chi^2/ndof \approx 840/492$.

The sources of systematic uncertainty and their evaluation are identical to those listed in Sec. VI. The main difference between the two energy regions is that, as previously remarked, the improved efficiency and background conditions in the $600 \leq E^*_\gamma \leq 1100$ MeV region of the $\Upsilon(3S)$ dataset lead to fit results that are more stable. For the $\chi_{b1,2}(2P)$-related measurements, the dominant systematic uncertainty is due to the conversion efficiency (3.3%), and all other sources are at the 1% level or less. For the $\eta_b(1S)$ signal, the largest uncertainty in the yield is related to the assumed $\eta_b(1S)$ width ($^{+17}_{-27}\%$). Of the remaining systematic uncertainties, the largest two are due to the MC parameterization ($\sim 15\%$) and bottomonium masses ($\sim 4\%$), both enhancing the yield in a positive direction. Uncertainty due to the background shape, the largest factor in the equivalent $\Upsilon(2S)$ analysis, is well controlled in the $\Upsilon(3S)$ dataset and contributes less than 3% to the total uncertainty. The uncertainty in E^*_γ is dominated by statistical uncertainty, and the largest systematic contribution is related to uncertainty in the E^*_γ scale via the uncertainty in the other bottomonium masses [27].

We measure $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P)) \times \mathcal{B}(\chi_{bJ}(2P) \to \gamma\Upsilon(1S)) = (4.0 \pm 2.2^{+1.2}_{-0.6}) \times 10^{-4}$, $(12.5 \pm 0.3^{+0.6}_{-0.5}) \times 10^{-3}$, and $(9.3 \pm 0.3 \pm 0.4) \times 10^{-3}$, for $J = 0$, 1 and 2, respectively. Using $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P))$ from the PDG [27], we derive $\mathcal{B}(\chi_{bJ}(2P) \to \gamma\Upsilon(1S)) = (0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1)\%$, $(9.9 \pm 0.3 \pm 0.4 \pm 0.9)\%$, and $(7.1 \pm 0.2 \pm 0.3 \pm 0.9)\%$, where the uncertainties are statistical, systematic, and from the uncertainty on $\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P))$, respectively. From these values, we calculate a 90% confidence level upper limit of $\mathcal{B}(\chi_{b0}(2P) \to \gamma\Upsilon(1S)) < 1.2\%$. As previously, we rescale the previous results [9, 11] using the relevant branching fractions [27] to produce the values for comparison in Table V. For the $\mathcal{B}(\chi_{b0}(2P) \to \gamma\Upsilon(1S))$ value from CUSB [9], we convert the result to an upper limit of $< 1.9\%$ at the 90% confidence level. Our $\chi_{bJ}(2P)$ transition results agree with the previous measurements, and are the most precise measurements to date. Assuming the peak near $E^*_\gamma = 900\,\mathrm{MeV}$ to be due to decays to $\eta_b(1S)$, our best fit result is $\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b(1S)) = (5.9 \pm 1.6^{+1.4}_{-1.6}) \times 10^{-4}$. The total significance of this result is $\sim 2.7\sigma$.

VIII. DISCUSSION

To conclude, we review the results of this study and their broader implications. The results for $\mathcal{B}(\chi_{bJ}(nP) \to \gamma\Upsilon(mS))$ presented here are the first derived directly from a measurement of the photon spectrum. For $J = 1$ and 2, we have made some of the most precise measurements of these branching fractions to date, thus helping to resolve some discrepancies between previous experimental results (*i.e.* in $\chi_{bJ}(2P) \to \gamma\Upsilon(2S)$ decays). Table VI shows a comparison of our results with some theoretical predictions [34]. These predictions are in reasonable agreement with our experimental results.

Our observations of $\Upsilon(3S) \to \gamma\chi_{b0,2}(1P)$ decays confirm the general features seen in previous measurements [13, 14, 36]: decays to $J = 1$ are suppressed compared to $J = 2$ and 0. This is unusual compared to all other $S \to P$ radiative transitions in the heavy quarkonium system measured thus far. As noted previously [45], the wavefunction overlap in the $\langle 3^3S_1 \mid r \mid 1^3P_J \rangle$ matrix elements is unusually small. Therefore, predictions for these decay rates are largely dependent on higher-order relativistic corrections and are thus sensitive to specific details of the chosen theoretical model. That said, the comparison of our results with a selection of theoretical predictions [45, 46] shown in Table VII (where we have converted our branching fraction measurements into partial widths) finds no good agreement with any particular model. Indeed, even the hierarchy of the decay rates ($J = 2 > 0 > 1$) is generally not well predicted. Further work, both theoretical and experimental, will be required to understand these decays.

The searches for $\eta_b(1S)$ and $\eta_b(2S)$ states using the converted photon energy spectrum are largely inconclusive. Over a range of approximately $9974 < m_{\eta_b(2S)} < 10015\,\mathrm{MeV}/c^2$, we find $\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b(2S)) < 1.9 \times 10^{-3}$. This value is consistent with, but does not improve upon, previous measurements [13]. Due to low efficiency and high background, no evidence for $\Upsilon(2S) \to \gamma\eta_b(1S)$ is found. In the $\Upsilon(3S)$ system, the most significant peaking structure in the E^*_γ energy region expected for the $\Upsilon(3S) \to \gamma\eta_b(1S)$ transition has $E^*_\gamma \approx 908\,\mathrm{MeV}$. If interpreted as an $\eta_b(1S)$ signal, this value trends toward to most recent potential model [47] and lattice [48] predictions, but we caution that the significance of this result is insufficient to draw such a conclusion regarding the $\eta_b(1S)$ mass. Taking advantage of the improved resolution from a converted photon technique to make a definitive measurement of the $\eta_b(1S)$ mass and width will require more data from future experiments.

IX. ACKNOWLEDGEMENTS

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TABLE V: Summary of the analysis of the $600 \leq E^*_\gamma \leq 1100$ MeV region of the $\Upsilon(3S)$ data. The E^*_γ column lists the transition energy assumed in this analysis, or in the case of $\Upsilon(3S) \to \gamma\eta_b(1S)$, the most significant ($\sim 2.7\sigma$) feature in the relevant E^*_γ region. Errors on the yield are statistical only. Regarding the derived branching fractions: the *BABAR* value is from this paper, while the CUSB and CLEO columns are derivations based on [9] and [11] using up-to-date secondary branching fractions from [27]. For the *BABAR* result, the listed uncertainties are statistical, systematic, and from the uncertainties on secondary branching fractions, respectively. Upper limits are given at the 90% confidence level. Dashes indicate no value has been measured in the quoted reference.

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) *BABAR*	CUSB	CLEO
$\chi_{b0}(2P) \to \gamma\Upsilon(1S)$	742.7	469^{+260}_{-259}	1.025	$0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1$ (< 1.2)	< 1.9	< 2.2
$\chi_{b1}(2P) \to \gamma\Upsilon(1S)$	764.1	14965^{+381}_{-383}	1.039	$9.9 \pm 0.3 \pm 0.4 \pm 0.9$	7.5 ± 1.3	10.4 ± 2.4
$\chi_{b2}(2P) \to \gamma\Upsilon(1S)$	776.4	11283^{+384}_{-385}	1.056	$7.1 \pm 0.2 \pm 0.3 \pm 0.9$	6.1 ± 1.2	7.7 ± 2.0
$\Upsilon(3S) \to \gamma\eta_b(1S)$	$907.9 \pm 2.8 \pm 0.9$	933^{+263}_{-262}	1.388	$0.059 \pm 0.016^{+0.014}_{-0.016}$	-	-

TABLE VI: Comparison of the experimental branching fraction results from this work (*BABAR*) and some theoretical predictions [34].

Decay	*BABAR* (%)	Theory (%)
$\mathcal{B}(\chi_{b0}(2P) \to \gamma\Upsilon(2S))$	(< 2.9)	1.27
$\mathcal{B}(\chi_{b1}(2P) \to \gamma\Upsilon(2S))$	19.1 ± 2.3	20.2
$\mathcal{B}(\chi_{b2}(2P) \to \gamma\Upsilon(2S))$	8.2 ± 1.4	10.1
$\mathcal{B}(\chi_{b0}(2P) \to \gamma\Upsilon(1S))$	(< 1.2)	0.96
$\mathcal{B}(\chi_{b1}(2P) \to \gamma\Upsilon(1S))$	9.9 ± 1.1	11.8
$\mathcal{B}(\chi_{b2}(2P) \to \gamma\Upsilon(1S))$	$7.1^{+1.0}_{-0.9}$	5.3
$\mathcal{B}(\chi_{b0}(1P) \to \gamma\Upsilon(1S))$	(< 4.6)	3.2
$\mathcal{B}(\chi_{b1}(1P) \to \gamma\Upsilon(1S))$	36.2 ± 2.8	46.1
$\mathcal{B}(\chi_{b2}(1P) \to \gamma\Upsilon(1S))$	$20.2^{+1.6}_{-1.8}$	22.2

TABLE VII: Comparison of our results with predictions [45, 46] for $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ decays. We convert our result into partial widths (in units of eV) using a total width of $\Gamma_{\Upsilon(3S)} = 20.32 \pm 1.85$ keV [27], absorbing this additional uncertainty into the total.

Source	$J = 0$	$J = 1$	$J = 2$
BABAR	55 ± 10	< 22	216 ± 25
Moxhay-Rosner	25	25	150
Grotch *et al.*	114	3.4	194
Daghighian-Silverman	16	100	650
Fulcher	10	20	30
Lähde	150	110	40
Ebert *et al.*	27	67	97

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TABLE VIII: Selection criteria for the $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ efficiency studies.

Quantity	$e^+e^-(\gamma)$	$\mu^+\mu^-(\gamma)$
nTRK	$= 4$	$= 4$
x^*_1	> 0.75	> 0.85
x^*_2	> 0.50	> 0.75
Greater $\lvert\cos\theta^*\rvert$	< 0.70	< 0.70
Lesser $\lvert\cos\theta^*\rvert$	< 0.65	< 0.65
α^* (°)	< 30	< 20

Appendix A: SYSTEMATIC UNCERTAINTIES ON MC-DETERMINED EFFICIENCIES

Branching fraction measurements in this analysis rely on MC-generated signal decays to determine the photon conversion and reconstruction efficiency. This efficiency is dependent on the detector material model. To evaluate a systematic effect due to the understanding of the detector in the simulation, a comparison of $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ samples between data and MC is made. Inclusive decays to an e^+e^- or $\mu^+\mu^-$ pair plus a photon are selected by requiring exactly four charged tracks in the event. The CM momentum of the two highest-momentum non-conversion tracks as a fraction of half of the CM beam energy (x^*_1, x^*_2), the higher and lower values of their CM polar angles ($|\cos\theta^*_{1,2}|$), and the CM acolinearity (α^*), are used as discriminating variables. We require $e^+e^-\gamma$ events to pass a predefined filter optimized to select Bhabha scattering events, and for the $\mu^+\mu^-\gamma$ events to fail this requirement. In cases of multiple candidates per event, the candidate with $m_{\ell^+\ell^-\gamma}$ closest to the CM beam energy is retained. The values for the selection criteria variables are summarized in Table VIII.

To avoid contamination from resonant decays (*e.g.* $\chi_{bJ}(nP) \to \gamma\Upsilon(mS)(\ell^+\ell^-)$, or $\Upsilon(nS) \to \ell^+\ell^-$ plus an extraneous photon), only the off-peak datasets are used for this study. The $e^+e^-(\gamma)$ MC sample uses the BHWIDE generator [49], while the $\mu^+\mu^-\gamma$ MC sample is generated using the KK2f generator [50]. The acceptance-based cross sections for these processes used in the MC generation are calculated separately from this analysis as part of standard luminosity measurements in BaBar.

A systematic correction to the MC-determined efficiency is determined by comparing the number of events expected from the luminosity-weighted MC samples with the total number reconstructed in the data. The uncertainty on this correction (dominantly statistical) is used as the systematic uncertainty in the efficiency due to the detector material model. The four samples ($e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ in off-peak $\Upsilon(2S)$ and $\Upsilon(3S)$ data) are averaged to calculate this number, as is justified by verifying excellent data-to-MC agreement across all relevant $\cos\theta$, E^*_γ, and ρ_γ ranges. Integrated over all events, the ratio of the data and MC is $96.3 \pm 3.1\%$ when modeling the photons converted in the detector material. This value is applied as a correction factor, with 3.3% (when considering cross section uncertainties of about 0.8%) taken as an estimate for the systematic uncertainty in the efficiency.

The MC-based signal efficiencies are also dependent on assumptions regarding inclusive bottomonium decays. The $nTRK$ requirements attempt to select multihadronic final states. A difference in $nTRK$ distributions between simulation and data could lead to an error on the reconstruction efficiency. To determine the size of this effect, the analysis is repeated with the requirements $nTRK$ equal to 5 or $nTRK$ equal to 6. The largest change in the efficiency-corrected yields for the most significant transitions ($\chi_{b1,2}(1,2P) \to \gamma\Upsilon(1,2S)$) is found to be 1.0%. We combine this value with the conversion-efficiency-related uncertainty described above, for a total systematic uncertainty of 3.4%.

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