SPECTROSCOPY AT B-FACTORIES USING HARD PHOTON EMISSION

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1. Introduction

Heavy quark physics is one of the frontier areas in studies of the fundamental properties of matter. That is why a new generation of $e^+e^-$ colliders (B-factories) has been designed. The CLEO-III\textsuperscript{1}, BELLE\textsuperscript{2}, and BABAR\textsuperscript{3} experiments are running since 1999. Their main goal is the precise investigation of the Cabibbo-Kobayashi-Maskawa matrix and, first of all, CP-violation in the b-quark sector. To achieve this goal, most of the time will be spent on running at the energy of the $\Upsilon(4S)$ resonance. At the same time there are physical tasks related with the spectroscopy of quarkonium systems which require scanning the energy region of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$. Such experiments were performed at DORIS, CESR, and VEPP-4\textsuperscript{5}. The main part of the bottomonium family has been observed, their masses and main decay modes have been measured. The list of experiments with the largest integrated luminosity is shown in Table 1. However, the accuracy of the measured parameters of the bottomonium family is not very high, preventing from the precise comparison between the data and different model predictions for the mass spectrum, decay rates, and dynamics of transitions. Moreover, some predicted states ($\eta_b(2S)$, $\eta_b(1S)$, $b(1P)$) have not yet been observed or are not well established. Thus, new experiments are necessary which will provide complete information about all states below the open flavor threshold.

Unfortunately, scans of the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ are not foreseen at asymmetric B-factory experiments. Of course, it can be done in a traditional way by CLEO-III but that will decrease the total integrated luminosity which is expected to be collected by CLEO-III at $\Upsilon(4S)$. That is why we consider a possibility to perform $\Upsilon$-spectroscopy studies at the $\Upsilon(4S)$ energy using the emission of a hard photon by the electron or the positron. This process is well known, it changes the value of the...
measured cross section (so called “radiative corrections”) and has to be taken into account in practically all $e^+e^-$ experiments.

Different possibilities of using radiative photons are now under intensive discussions. It was suggested to measure the longitudinal structure function $F_L(x, Q^2)$ at HERA using events with the emission of a hard photon collinear to the incident lepton beam [10, 11]. Such a measurement has recently been performed by H1 [12]. Other authors [13, 14, 15, 16] suggest to use a similar process for precise determination of $R$ at the DAΦNE $\phi$-factory. In the present work the following reaction has been studied:

$$e^+e^- \rightarrow \gamma V \rightarrow \gamma f,$$

where $V$ is one of the vector resonances $\Upsilon(3S)$, $\Upsilon(2S)$, $\Upsilon(1S)$ etc. decaying to a final state $f$. Our main task is to show the practical feasibility of using such processes for spectroscopy studies at B-factories in near future.

2. Calculation of the Production Cross Sections

At first order of quantum electrodynamics (QED) the process (1) is described by two diagrams (Fig.1). The Born term for this process can be obtained using the quasi-real electron method [13, 14].

$$\frac{d\sigma(s,x)}{dx
d\cos \theta} = \frac{2\alpha}{\pi x} \left(1 - x + \frac{x^2}{2}\right) \frac{\sin^2 \theta}{(\sin^2 \theta + \frac{m_e^2}{E^2} \cos^2 \theta)^2} \cdot \sigma_0(s(1 - x)), \quad (2)$$

where $s = 4E^2$, $E$ is the beam energy in the center of mass system of the electron and positron, $m_e$ is the electron mass, $\alpha$ is the fine structure constant, $x = E_\gamma/E$ is the fraction of the beam energy taken by the radiative photon with the energy $E_\gamma$, $\theta$ is the photon emission angle with respect to the beam ($0 < \theta < \pi$), $\sigma_0(s)$ is the cross section of hadronic production in $e^+e^-$ annihilation.

If one performs integration over $\theta$ in (2), the following energy dependence is
obtained:
\[
\frac{d\sigma(s, x)}{dx} = W(s, x) \cdot \sigma_0(s(1 - x)),
\]
where \( W(s, x) \) is the probability function of the photon emission which can be written:
\[
W(s, x) = \frac{2\alpha}{\pi} \cdot (L - 1) \cdot (1 - x + \frac{x^2}{2}), \quad L = 2 \ln \frac{\sqrt{s}}{m_e}.
\]

The Born cross section of the narrow vector resonance \( V \) production is given by the standard Breit-Wigner formula
\[
\sigma_0(s) = \frac{12\pi B_{ee}}{m_V^2} \cdot \frac{m_V^2 \Gamma_V^2}{(s - m_V^2)^2 + m_V^2 \Gamma_V^2},
\]
where \( m_V \) and \( \Gamma_V \) are the resonance mass and width respectively, \( B_{ee} \) is the branching fraction of the \( V \to e^+e^- \) decay. If the resonance is narrow, the photon energy spectrum in reaction (1) is also narrow. The central value of the photon energy fraction is \( x_V = (1 - m_V^2/s) \). For a very narrow resonance, one can replace
\[
\frac{m_V \Gamma_V}{(s - m_V^2)^2 + m_V^2 \Gamma_V^2} \to \pi \delta(s - m_V^2)
\]

The total cross section \( \sigma_V(s) \) of the process (1) can be found by the integration of (3) in the region around \( x_V \) using (5) and (6)
\[
\sigma_V(s) = \frac{12\pi^2 B_{ee} \Gamma_V}{m_V \cdot s} \cdot W(s, x_V).
\]

Assuming that the experiment is carried out at the \( \Upsilon(4S) \) energy, the production cross sections of vector mesons with quantum numbers \( J^{PC} = 1^{--} \) can be calculated using (7) and PDG values for the meson masses and widths. The results are shown in Table 2. In addition, we present in this Table the numbers of produced events which correspond to a collected integrated luminosity of 10 fb\(^{-1}\).

These results demonstrate that radiative production cross sections have the same order of magnitude for all quarkonium states. These values show the practical feasibility of using such processes for spectroscopy studies at B-factories in near future.
Table 2. Cross sections for radiative production of $J^{PC} = 1^{--}$ mesons at the $\Upsilon(4S)$ energy: $\sigma_I^V$ is the cross section calculated at first order; $\sigma_{II}^V$ is the cross section calculated with leading second order corrections; $N_{total}$ is the total number of mesons produced in the experiment with the integrated luminosity of $10 fb^{-1}$; $N_{\gamma l^+ l^-}$ is the number of lepton decays for radiative production. The estimation of the $\Upsilon(4S)$ production cross section and the number of produced radiative Bhabha events and $\tau$-lepton pairs at $\Upsilon(4S)$ are shown for comparison.

| Meson  | $\sigma_I^V (nb)$ | $\sigma_{II}^V (nb)$ | $N_{total}, 10^6$ | $N_{\gamma e^+ e^-}, 10^3$ | $N_{\gamma \tau^+ \tau^-}, 10^4$ |
|--------|-------------------|----------------------|-------------------|---------------------------|-----------------------------|
| $\Upsilon(4S)$ | -                 | 3.40                 | 34                | $4 \cdot 10^6$            | $1.1 \cdot 10^4$            |
| $\Upsilon(3S)$ | 0.038             | 0.031                | 0.31              | 5.59                      | 5.55                        |
| $\Upsilon(2S)$ | 0.016             | 0.015                | 0.15              | 1.83                      | 1.81                        |
| $\Upsilon(1S)$ | 0.021             | 0.019                | 0.19              | 4.71                      | 4.67                        |
| $\psi(2S)$     | 0.013             | 0.014                | 0.14              | 1.22                      | 0.47                        |
| $J/\psi(1S)$   | 0.034             | 0.036                | 0.36              | 21.5                      | 0                           |
| $\phi$         | 0.024             | 0.027                | 0.27              | 0.08                      | 0                           |
| $\omega$       | 0.014             | 0.016                | 0.16              | 0.01                      | 0                           |
| $\rho$         | 0.160             | 0.182                | 1.82              | 0.08                      | 0                           |

At the same time we have to point out that reaction (1) could provide some background for various processes which will be studied at B-factory experiments, particularly for two photon processes and $\tau$-lepton decays. That is why such processes have to be investigated at asymmetric B-factories, even if CLEO-III will perform energy scan of $\Upsilon(2S)$ or $\Upsilon(3S)$ regions with a high integrated luminosity.

The expression for the differential cross sections (2) allows to estimate that about 50% of photons are emitted within the angle of 20 mrad to the beam axis. Using the parameters of B-factories (5), one can calculate the values of velocity in radiative production (Table 3) for reaction (1) in the case when photons are directed along the beam. Kinematic conditions at B-factories are slightly different, so produced vector mesons will have different boosts. Note that $\Upsilon$-mesons at asymmetric B-factories will fly in the direction of the high energy beam. Light mesons will have both directions.

Table 3. Velocity $\beta = v/c$ of the meson in the radiative production at B-factories. For the asymmetric factories two values are shown corresponding to the radiative photon emitted by the positron or by the electron. Photon direction coincides with the beam. The values of the $\Upsilon(4S)$ velocity are shown for comparison.

| Factory | CESR | KEKB | PEP-II |
|---------|------|------|--------|
| $\Upsilon(4S)$ | 0    | 0.391 | 0.488  |
| $\Upsilon(3S)$ | 0.023 | 0.410 | 0.373  | 0.503 | 0.472 |
| $\Upsilon(2S)$ | 0.056 | 0.436 | 0.344  | 0.527 | 0.447 |
| $\Upsilon(1S)$ | 0.113 | 0.482 | 0.292  | 0.567 | 0.399 |
| $\psi(2S)$    | 0.784 | 0.899 | 0.566  | 0.920 | 0.478 |
| $J/\psi(1S)$  | 0.843 | 0.928 | 0.673  | 0.942 | 0.601 |
| $\phi$        | 0.982 | 0.992 | 0.958  | 0.994 | 0.947 |
| $\omega$      | 0.989 | 0.995 | 0.975  | 0.996 | 0.969 |
| $\rho$        | 0.990 | 0.995 | 0.976  | 0.996 | 0.970 |
3. Remarks on the Leading $\alpha^2$ Corrections

In the previous section the cross section at first order in $\alpha$ has been used to estimate the main effects of hard photon emission. Expressions which take into account the leading $\alpha^2$ contributions are also well known. Equation (3) gives a correct estimate for the radiative photon emission cross section with about 10-20% precision. Two important improvements are necessary in this formula if better accuracy is required. First of all, the cross section as given by Eq. (3) is infrared divergent. To cure this shortcoming, it is necessary to sum all diagrams with soft multi-photon emission. It is well known that this procedure leads to the soft-photon exponent. A practically convenient (but not completely correct) recipe for this exponentiation in a narrow resonance case was given in. Exponentiation of soft photons in the case of Bonneau and Martin cross section was further considered with an explicit Monte Carlo algorithm for this exponentiation.

Some second order corrections containing large logarithms can also contribute up to a several percent level. The structure function method suggested in is a popular tool to calculate finite-order leading logarithmic corrections. This formalism also gives the factorized form (3) for the radiative photon emission cross section. $W(s, x)$ function, the so called QED “radiator”, consists of two parts. The exponentiated part accounts for soft multi-photon emission, while the remaining one takes into account hard collinear bremsstrahlung in the leading logarithmic approximation. Up to order $\alpha^2$, the radiator looks like

$$ W(s, x) = \Delta \cdot x^{\beta - 1} \left( - \frac{\beta}{2} (2 - x) + \frac{\beta^2}{8} \left\{ (2 - x) [3 \ln (1 - x) - 4 \ln x] - 4 \frac{\ln (1 - x)}{x} - 6 + x \right\} \right), $$

$$ \Delta = 1 + \frac{\alpha}{\pi} \left( \frac{3}{2} L + \frac{1}{3} \pi^2 - 2 \right) + \left( \frac{\alpha}{\pi} \right)^2 \delta_2, $$

$$ \delta_2 = \left( \frac{9}{8} - 2 \zeta_2 \right) L^2 - \left( \frac{45}{16} - \frac{11}{2} \zeta_2 - 3 \zeta_3 \right) L - \left( \frac{6}{5} \zeta_2^2 - \frac{9}{2} \zeta_3 - 6 \zeta_2 \ln 2 + \frac{3}{8} \zeta_2 + \frac{57}{12} \right), $$

$$ \beta = \frac{2\alpha}{\pi} (L - 1), \quad \zeta_2 = 1.64593407, \quad \zeta_3 = 1.2620569. \quad (8) $$

Note that some $\alpha^3$ contributions in the QED radiator are also known but they are irrelevant for our goals. Using expression (3) and formula (8), one can obtain the differential cross section of radiative production at second order in $\alpha$. The corresponding total cross section is given by the relation (3). The results of calculations taking into account leading $\alpha^2$ corrections are shown in Table 2. The difference with the first order estimation is 20% for $\Upsilon(3S)$ production and (5-10)% for the production of other resonances.

The angular distribution of the emitted photon given by Eq. (3) is valid for soft enough photons and small emission angles only. A more general result which can
be obtained by the method of Bonneau and Martin up to \( m_e^2/s \) terms, is

\[
\frac{d\sigma(s, x)}{dx \; d\cos\theta} = \frac{2\alpha}{\pi x} \cdot \left(1 - x + \frac{x^2}{2}\right) \cdot \sigma_0(s(1 - x)) \cdot P(\theta),
\]

\[
P(\theta) = \frac{\sin^2\theta - \frac{x^2 \sin^4\theta}{2(x^2 - 2x + 2)} - \frac{m_e^2}{E^2} \frac{(1 - 2x) \sin^2\theta - x^2 \cos^4\theta}{x^2 - 2x + 2}}{\left(\sin^2\theta + \frac{m_e^2}{E^2} \cos^2\theta\right)^2}. \tag{9}
\]

This result is in agreement with one of the first works devoted to the radiative process \( e^+e^- \rightarrow \mu^+\mu^-\gamma \). The \( m_e^2/s \) terms in (9) become important for very small angles \( \theta \) only. Nevertheless, since these terms are drastically peaked, they give non-negligible contribution to \( d\sigma/dx \) and their presence is necessary to obtain the correct form at order \( \alpha \) for this differential cross section, as given by equations (3) and (4). Note that expressions presented in Refs. 15, 16, 29 do not include such terms.

From (9) one can obtain the probability for the hard photon to be emitted inside the cone of opening the angle \( \theta_m \)

\[
\mathcal{P}(0 \leq \theta \leq \theta_m) = \frac{h(\theta_m)}{h(\pi)}, \quad h(\theta_m) = \int_0^{\theta_m} P(\theta) \sin\theta d\theta, \tag{10}
\]

where

\[
h(\theta) = \frac{L - 1}{2} + \frac{m_e^2}{2E^2} \frac{\cos\theta}{\sin^2\theta + \frac{m_e^2}{E^2} \cos^2\theta} - \frac{1}{2} \ln \frac{1 + \sqrt{1 - \frac{m_e^2}{E^2} \cos\theta}}{1 - \sqrt{1 - \frac{m_e^2}{E^2} \cos\theta}} + \frac{x^2 \cos\theta}{2(x^2 - 2x + 2)} \left(1 - \frac{m_e^2}{E^2} \frac{1}{\sin^2\theta + \frac{m_e^2}{E^2} \cos^2\theta}\right). \tag{11}
\]

Note that \( h(\pi) = L - 1 \).

4. Prospects for Spectroscopy of Bottomonium

To study the bottomonium spectroscopy, two types of events can be considered for which background will be small. The first one can be referred to as “tagged photon” events. In these events a hard photon is emitted at a large angle with respect to the beam axis and is recorded by the main calorimeter of the detector. Using the high energy and position resolution of the calorimeter for photons, one can reconstruct the recoil energy of the hadronic system in the reaction (3) and thereby precisely identify the produced vector meson \( V \). In this case the investigation of its decay modes becomes possible without requiring that all final particles from the \( V \) decay be detected. If another hard collinear photon is additionally emitted, the recoil energy spectrum is smeared and acquires some tails, but this effect should not be large.

Formulae (10) and (11) allow to estimate the “tagged photon” detection efficiency for the processes (3). To do that, the probability of the hard photon emission at angle \( \theta \) relative to the beam direction is calculated \( (\theta_{\min} < \theta < \theta_{\max}) \).
The energy of the photon is fixed by the mass of the produced resonance \( x = x_V \). The maximum and minimum angles \( \theta_{\text{max}}, \theta_{\text{min}} \) are defined by the geometry of the electromagnetic calorimeter of the specific detector. Results of the calculation are shown in Table 4.

Table 4. The detection efficiency for the hard photon in calorimeters of the B-factory detectors.

| Detector | \( \theta_{\text{min}}, \text{degrees} \) | \( \theta_{\text{max}}, \text{degrees} \) | Meson | \( \epsilon, \% \) |
|----------|--------------------------------|---------------------------------|-------|----------------|
|          |                                |                                 | \( \Upsilon(3S) \) | 13.9           |
|          |                                |                                 | \( \Upsilon(2S) \) | 13.9           |
|          |                                |                                 | \( \Upsilon(1S) \) | 13.8           |
|          |                                |                                 | \( \Psi(2S) \)   | 10.5           |
| CLEO-III | 30.0                           | 150.0                           | \( J/\Psi(1S) \) | 10.1           |
|          |                                |                                 | \( \phi \)       | 9.5            |
|          |                                |                                 | \( \omega \)     | 9.4            |
|          |                                |                                 | \( \rho \)       | 9.4            |
|          |                                |                                 | \( \Upsilon(3S) \) | 20.0           |
|          |                                |                                 | \( \Upsilon(2S) \) | 19.9           |
|          |                                |                                 | \( \Upsilon(1S) \) | 19.8           |
|          |                                |                                 | \( \Psi(2S) \)   | 16.1           |
| BELLE    | 18.3                           | 163.7                           | \( J/\Psi(1S) \) | 15.8           |
|          |                                |                                 | \( \phi \)       | 15.0           |
|          |                                |                                 | \( \omega \)     | 15.0           |
|          |                                |                                 | \( \rho \)       | 15.0           |
|          |                                |                                 | \( \Upsilon(3S) \) | 15.9           |
|          |                                |                                 | \( \Upsilon(2S) \) | 15.9           |
|          |                                |                                 | \( \Upsilon(1S) \) | 15.8           |
|          |                                |                                 | \( \Psi(2S) \)   | 12.3           |
| BABAR    | 26.5                           | 156.3                           | \( J/\Psi(1S) \) | 12.0           |
|          |                                |                                 | \( \phi \)       | 11.2           |
|          |                                |                                 | \( \omega \)     | 11.2           |
|          |                                |                                 | \( \rho \)       | 11.2           |

As mentioned above, the main part of hard photons is emitted along the beam axis. Thus, this photon will not fire the detector calorimeter. In this case complete reconstruction of the hadronic system from the reaction is necessary. It was recently shown by CLEO-II that, studying events with lepton and pion pairs in the final state, one can obtain a practically clean sample of pion transitions between \( \Upsilon(2S) \) and \( \Upsilon(1S) \) resonances. The estimated number of events of such type in the reaction \( (4) \) at \( \Upsilon(4S) \) is shown in Table 5.

Table 5. The estimated number of events of hadron transitions with two pions and a lepton pair in the final state for an experiment with the integrated luminosity of 10 \( fb^{-1} \).

| Reaction | N events |
|----------|----------|
| \( \Upsilon(3S) \to \Upsilon(2S)\pi\pi \to l^+l^-\pi\pi \) | 428 |
| \( \Upsilon(3S) \to \Upsilon(1S)\pi\pi \to l^+l^-\pi\pi \) | 1248 |
| \( \Upsilon(2S) \to \Upsilon(1S)\pi\pi \to l^+l^-\pi\pi \) | 2208 |

One of the important tasks for the bottomonium spectroscopy is to study radiative transitions, when \( \Upsilon(3S) \) or \( \Upsilon(2S) \) decays to one of the \( \chi_b \) states and after another radiative decay \( \Upsilon(2S) \) or \( \Upsilon(1S) \) is produced. If the final \( \Upsilon(2S) \) or \( \Upsilon(1S) \)
decays into a lepton pair, these reactions possess a clear signature “two photons and lepton pair” allowing obvious background rejection. The estimated number of produced events with a gamma transition is shown in Table 6.

Table 6. The estimated number of radiative decay events with two photons and a lepton pair in the final state for experiment with the integrated luminosity of $10 \text{ fb}^{-1}$.

| Reaction | N events |
|----------|----------|
| $\Upsilon(3S) \rightarrow \chi_{b2}(2P)\gamma \rightarrow \Upsilon(2S)\gamma\gamma$ | 164 |
| $\Upsilon(3S) \rightarrow \chi_{b1}(2P)\gamma \rightarrow \Upsilon(2S)\gamma\gamma$ | 212 |
| $\Upsilon(3S) \rightarrow \chi_{b0}(2P)\gamma \rightarrow \Upsilon(2S)\gamma\gamma$ | 22 |
| $\Upsilon(3S) \rightarrow \chi_{b2}(2P)\gamma \rightarrow \Upsilon(1S)\gamma\gamma$ | 183 |
| $\Upsilon(3S) \rightarrow \chi_{b1}(2P)\gamma \rightarrow \Upsilon(1S)\gamma\gamma$ | 22 |
| $\Upsilon(3S) \rightarrow \chi_{b0}(2P)\gamma \rightarrow \Upsilon(1S)\gamma\gamma$ | 9 |
| $\Upsilon(2S) \rightarrow \chi_{b2}(1P)\gamma \rightarrow \Upsilon(1S)\gamma\gamma$ | 122 |
| $\Upsilon(2S) \rightarrow \chi_{b1}(1P)\gamma \rightarrow \Upsilon(1S)\gamma\gamma$ | 192 |
| $\Upsilon(2S) \rightarrow \chi_{b0}(1P)\gamma \rightarrow \Upsilon(1S)\gamma\gamma$ | 10 |

The number of estimated events with $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ decays shown in Table 6 is smaller than the one collected by a standard method of scanning each resonance in CLEO-II experiments. But the integrated luminosity to be collected by the designed B-factories is at least one order of magnitude higher than that in our estimations. This means that reaction (1) can serve as a real source of all bottomonium states and provide new independent information complementary to the existing data as well as to that expected from future experiments with CLEO-III.

5. Conclusion

Estimations performed in this work have demonstrated feasibility of using a radiative photon for studies of the bottomonium spectroscopy at B-factories. These processes have to be taken into account as a possible background for various reactions which will be studied in these experiments at the $\Upsilon(4S)$ energy. If the integrated luminosity of about $100 \text{ fb}^{-1}$ is collected, the number of events for spectroscopy studies with clean signature will be higher than that collected now by the traditional method of scanning the resonance energy range.

The same method can be considered to study $\rho$ and $\omega$ meson decays at the DAΦNE $\phi$-factory. For example, for an integrated luminosity of about $300 \text{ pb}^{-1}$, the number of $\omega\gamma$ events is $10^6$ and that of $\rho\gamma$ is $10^7$.

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