Indications for the Existence of Chiral Particles: the Axial-Vector $D^\chi_1$ and the Scalar $B^\chi_0$

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In a covariant level-classification scheme of hadrons proposed recently, the existence of "chiral particles", scalar and axial-vector mesons as the partners of the ground-state pseudo-scalar and vector mesons, respectively, were predicted in $D$ and $B$ meson systems, realizing a linear representation of chiral symmetry concerning the light quark. In this work we reanalyze the $D^*\pi$ mass spectra obtained through $\Upsilon(4S)$ and $Z^0$ decay and the $B\pi$ spectra obtained through $Z^0$ decay to show the possibility of the existence of $D^\chi_1$ and $B^\chi_0$, respectively.

§1. Introduction

The level classification of hadrons has been carried out rather successfully on the basis of the non-relativistic quark model (NRQM) for the past four decades. However, this non-relativistic scheme seems now to be confronted with a serious difficulty: The existence$^{1,2}$ of the light-mass iso-scalar scalar meson to be identified with $\sigma$, the chiral partner of the $\pi$ meson as a Nambu-Goldstone boson, has become widely accepted.$^5$ Subsequently, the possible existence of the $\kappa(900)$ meson,$^6$ the iso-spinor scalar meson, has been pointed out. Thus we are able to naturally identify the $\sigma$-meson nonet$^7$ with the members $\{\sigma(600), \kappa(900), a_0(980), f_0(980)\}$.

The mass values ($\leq 1$ GeV) of this scalar nonet are in the region of $q\bar{q}$ ground states in NRQM, while there are no seats for scalars in this model. This has aroused recently a hot controversy concerning the quark configuration of the $\sigma$ nonet.

Within this context, we have proposed a new level-classification scheme,$^8,9$ which has a relativistically covariant framework and is in conformity with the approximate chiral symmetry. In this new classification scheme, the "chiral states", which are not included within the framework of the NRQM, are expected to exist in the lower mass region, and the $\sigma$-nonet is naturally assigned as the $(q\bar{q})$ relativistic S-wave chiral state. In a heavy-light quark meson system, it is believed that the approximate chiral symmetry of the light quark is valid, and the new level-classification scheme predicts the existence of chiral states,$^{10}$ scalar mesons...
and axial-vector mesons, in addition to the conventional pseudo-scalar and vector mesons, in the ground states. The purpose of this work is to investigate phenomenologically the possibility of the existence of the chiral axial-vector meson $D_1^\chi$ in the $D$ meson system and the chiral scalar meson $B_0^\chi$ in the $B$ meson system by re-analyzing some experimental data reported previously.\(^\dagger\)

\section{Analysis of $D^\ast\pi$ mass spectra in the search for $D_1^\chi$}

\subsection{Experimental data and project for reanalysis}

(Experimental data to be analyzed)

As the experimental data\(^{12,13}\) to be re-analyzed, we choose the mass spectra of the $D^\ast\pi$ system obtained through the two processes

\begin{align*}
\text{CLEO II : } & e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow D^\ast\pi^- + \cdots, & (2.1) \\
\text{DELPHI : } & e^+ + e^- \rightarrow Z^0 \rightarrow D^\ast\pi^- + \cdots, & (2.2)
\end{align*}

which have at least the level of statistical accuracy necessary for meaningful analysis. We consider two kinds of CLEO data on the process Eq. (2.1), CLEO (a) and CLEO (b); the former are selected specifically so as to relatively stress the conventional axial-vector meson $D_0^1$, while the latter comprise all the relevant data.

As a description of the irrelevant background, which comes from all processes other than the decay processes of the relevant resonant particles, the CLEO group set up the formula

\begin{equation}
B \cdot G. = \alpha (\Delta M)^\beta \times \exp(-\gamma_1 (\Delta M) - \gamma_2 (\Delta M)^2 - \gamma_3 (\Delta M)^3),
\end{equation}

with the fitting parameters $\alpha$, $\beta$, $\gamma_1$, $\gamma_2$, $\gamma_3$, while the DELPHI group has applied formula similar to Eq. (2.3) with fitting parameters $\alpha$, $\beta$, $\gamma_1$, setting $\gamma_2 = \gamma_3 = 0$. We employ the formula to Eq. (2.3) with the parameters $\alpha$, $\beta$, $\gamma_1$, $\gamma_2$, $\gamma_3$ for the background, taking into account the possible effects of intermediate $D_1^\chi$ production.

(Relevant intermediate resonances)

The conventional three $(c\bar{q})$-$P$ wave mesons may contribute, as intermediate states, to the final $D^\ast\pi^-$ system with the respective angular momenta $l = 0, 1, 2$ as

\begin{align*}
D_1^* & \rightarrow D^\ast + \pi^- \quad (S\text{-wave}) , & (2.4) \\
D_1 & \rightarrow D^\ast + \pi^- \quad (D\text{-wave}) , & (2.5) \\
D_2^* & \rightarrow D^\ast + \pi^- \quad (D\text{-wave}) , & (2.6)
\end{align*}

where $D_1^\ast$, $D_1$ and $D_2^\ast$ have, respectively, $j_q L_J = \frac{1}{2} P_1$, $\frac{3}{2} P_1$ and $\frac{3}{2} P_2$ (here, $j_q = S_q + L$ is the total angular momentum of the light quark), and the respective partial wave states in Eqs. (2.4)-(2.6) are deduced from the heavy quark symmetry (HQS). In this work, the possible contribution from, in addition to the above conventional

\(^\dagger\) Preliminary results from the analysis of $D_1^\chi$ were reported at the conference Hadron 2001 at Protvino.\(^{11}\)
resonances, the chiral axial-vector meson $D_1^\chi$ is taken into account as
\[ D_1^\chi \rightarrow D^{*+} + \pi^- \quad \text{(S-wave)} , \]
where we have inferred that the S-wave decay is dominant because of the small $Q$ value.

Of the three resonances in Eqs. (2.4)–(2.6), the $D_1$ and $D_2^*$, decaying into the $D$-wave, have comparatively small decay widths $\sim 20$ MeV, while $D_1^*$, decaying into the S-wave, has a large width, $\sim 300$ MeV, reflecting the physical situation that all three resonances have small $Q$ values and that the widths contain the kinematical factor $\Gamma \propto P^{2l+1}$ ($P$ being the relative momentum of the final system).

Because of its large width, the contribution of $D_1^*$ is difficult to be discriminated from the background, and it was treated as being included in the background in the original analysis by the experimental groups. In this work we follow this prescription.

Thus, in order to analyze the relevant mass spectra, we take into account the three resonances $D_1$, $D_2^*$ and $D_1^\chi$.

(Method of analysis)

We apply the VMW method, where the absolute amplitude squared is given by
\[ |M(s)|^2 = \sum_i |r_i \Delta_i(s)|^2 + B. \ G., \]
\[ \Delta_i \equiv -m_i \Gamma_i / (s - m_i^2 + i m_i \Gamma_i) . \]
Here the summation with respect to the suffix $i$ is over the resonant particles $D_1$, $D_2^*$ and $D_1^\chi$, $m_i(\Gamma_i)$ represents their masses (widths), and $r_i$ represents their production strength.

The relevant mass spectrum is given by
\[ \Gamma(s) = \frac{1}{2\sqrt{s}} \int \frac{d^3P_D d^3P_\pi}{(2\pi)^3 2 E_D (2\pi)^3 2 E_\pi} \times (2\pi)^4 \delta^{(4)}(P - P_D - p_\pi) |M(s)|^2 , \]
where $s \equiv -(P_\mu)^2$, and $P_\mu$ is the total 4-momentum of the system.

(Project for applying $\chi^2$-analysis)

In order to obtain the least-$\chi^2$ solution with respect to the parameters we employ, we restrict the values of the resonance masses and widths as stated in Table I.

The regions for $D_1$ and $D_2^*$ are determined from the center values and errors of the respective resonances reported in the Particle Data Group (PDG) table. Regarding the chiral particle $D_1^\chi$, some structure that cannot be accounted for as the background in the regions centered near $m \sim 2300$ MeV, (which is seen in all three sets of experimental data, CLEO (a) and (b) and DELPHI) is identified as being due to the production of $D_1^\chi$. The restrictions on $D_1^\chi$ come simply from inspection of this structure.
We carried out two kinds of $\chi^2$-fitting of the mass spectra, one with $D_1^X$ and the other without $D_1^X$. Below we compare with their results.

2.2. Results of analysis

The results of our analysis in cases both with and without $D_1^X$, are displayed in Figs. 1 and 2: The fitted curves compared with the data of CLEO (b), DELPHI and CLEO (a) are given, respectively, in Figs. 1 and 2 in cases both with and without $D_1^X$.

Actually, we performed our analysis in the two steps (taking into account the difference in statistical accuracy of the different data sets). First, we fit CLEO (b) and DELPHI together, as shown in Fig. 1, and then, we fit CLEO (a), as shown in Fig. 2, with fixed values of the resonance mass and width obtained from the first fitting. The respective contributions from $D_1^X$, $D_1$, $D_2^*$ and the B. G. are also shown.

(a) CLEO (b) with $D_1^X$
(b) CLEO (b) without $D_1^X$
(c) DELPHI with $D_1^X$
(d) DELPHI without $D_1^X$

Fig. 1. Fitted curves in the case with [without] $D_1^X$ and the experimental data of CLEO (b) and DELPHI are plotted, respectively, in (a) and (c) [(b) and (d)].
Fig. 2. Fitted curves in the case with (without) $D^X_1$ are, for reference, given in comparison with experimental data, CLEO(a), where the values of mass and width of relevant resonances are determined in the analysis of CLEO(b) and DELPHI.

The obtained values of the mass and the width of the relevant resonances are collected in Table II. The values of $D_1$ and $D_2^*$ are close to those given in the PDG table.

In Table III the values of $\chi^2$ and of $\tilde{\chi}^2$ ($\equiv \chi^2/[$No. of data points – No. of param.$]$) in the respective steps of the fitting are also given.

Table II. Fitted values of mass and width of resonances (in MeV).

<table>
<thead>
<tr>
<th></th>
<th>$D^X_1$</th>
<th>$D_1$</th>
<th>$D_2^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>2312</td>
<td>2421</td>
<td>2465</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>23.03</td>
<td>30.73</td>
<td>42.54</td>
</tr>
</tbody>
</table>

Table III. Values of $\chi^2$ and $\tilde{\chi}^2$.

<table>
<thead>
<tr>
<th></th>
<th>(A) with $D^X_1$</th>
<th>(B) without $D^X_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO (b) DELPHI</td>
<td>CLEO (a) DELPHI</td>
<td>CLEO (b) DELPHI</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>110 (140 – 20) = 0.923</td>
<td>80.6 (70 – 8) = 1.30</td>
</tr>
<tr>
<td>$\tilde{\chi}^2$</td>
<td>59.51</td>
<td>51.28</td>
</tr>
</tbody>
</table>

Through inspection of the fitted curves in Fig. 1, we can conclude that our results give some evidence for the existence of $D^X_1$, although there is no significant improvement on the reduced $\chi^2$ given in Table III.

§3. Analysis of $B\pi$ mass spectra in the search for $B^X_0$

3.1. Experimental data and project for reanalysis

(Experimental data to be analyzed)

As the experimental data to be reanalyzed in this case, we choose the mass spectra of the $B\pi$ system obtained through $Z^0$ boson decay,

$$e^+ + e^- \rightarrow Z^0 \rightarrow B\pi + \cdots,$$  \hspace{1cm} (3.1)
by L3 collaboration\textsuperscript{14}) which have comparatively high statistical accuracy. We also consider the data of the ALEPH collaboration,\textsuperscript{15}) with low statistical accuracy, for supplementary analysis. The original data are inclusive, and the relevant exclusive mass spectra of the $B\pi$ system are obtained by subtracting from the original ones a background of the form

\[ B. \ G. = P_1(\Delta M)^{P_3} \exp \left[ P_4(\Delta M) + P_5(\Delta M)^2 + P_6(\Delta M)^3 \right], \quad (3.2) \]

with fitting parameters $P_i \ (i = 1, 2, \cdots, 6)$. We apply the same formula to Eq. (3.2) for the background, taking into account the possible effects of intermediate $B\chi_0$ production.

(Relevant intermediate resonances)

The conventional two $(b\bar{q})$-$P$ wave mesons may contribute directly, as intermediate states, to the final $B\pi$ system with the respective angular momenta $l = 0, 2$ as

Direct Reson. Process $B_0^* \rightarrow B + \pi$ (S-wave), \quad (3.3)

$B_2^* \rightarrow B + \pi$ (D-wave), \quad (3.4)

where $B_0^*$ and $B_2^*$ have, respectively, $j_qL_J = \frac{1}{2}P_0$ and $\frac{3}{2}P_2$ (here $j_q = S_q + L$ is the total angular momentum of the light quark).

In this work, a possible direct contribution from, in addition to the above conventional resonances, the chiral scalar meson $B_0^X$ is taken into account as

Direct Reson. Process $B_0^X \rightarrow B + \pi$ (S-wave). \quad (3.5)

Regarding the chiral particle $B_0^X$, structure that cannot be accounted for by the background around the mass $m \sim 5550$ MeV, which is seen in both the data of L3 and ALEPH, is identified as being due to production of $B_0^X$.

In the experiment under consideration the low energy $\gamma$ was not observed. Accordingly, we must take into account the background process from the intermediate resonances, decaying into $B^* + \pi$ (successively, $B^*$ decays into $B$ and missing $\gamma$).

Backgd. Reson. Process $B_1^* \rightarrow B^* + \pi$ (S-wave), \quad (3.6)

$B_1 \rightarrow B^* + \pi$ (D-wave), \quad (3.7)

$B_2^* \rightarrow B^* + \pi$ (D-wave), \quad (3.8)

$B^* \rightarrow B + \gamma$. \quad (3.9)

(Formulas for analysis)

We apply the VMW method, where the absolute amplitude squared is given by

\[ |M(s)|^2 = \left\{ |r_1\Delta B_0^X(s) + r_2e^{i\theta}\Delta B_0^X(s)|^2 + |r_3\Delta B_2^X(s)|^2 \right\} + \left\{ |r_4\Delta B_1^X(s)|^2 + |r_5\Delta B_2^X(s)|^2 + |r_6\Delta B_1^X(s)|^2 \right\} \]

\[ \Delta_i(s) \equiv \frac{-m_i \Gamma_i}{s - m_i^2 + im_i \Gamma_i}. \quad (i \ denoting \ respective \ resonances) \quad (3.10) \]

\[ \Delta_i(s) \equiv \frac{-m_i \Gamma_i}{s - m_i^2 + im_i \Gamma_i}. \quad (i \ denoting \ respective \ resonances) \quad (3.11) \]
Here, the first (second) term represents the contributions from the direct (background) resonance processes Eqs. (3.3)–(3.5) [Eqs. (3.6)–(3.8)], $m_i(\Gamma_i)$ represents the mass (width) of the $i$th resonance, and $r_i$ represents its production strength. In Eq. (3.10), a possible interference effect between the two direct decay processes of $B_0^\chi$ [Eq. (3.3)] and $B_0^\chi$ [Eq. (3.5)] are taken into account, while no interference effects among any background processes Eqs. (3.6)–(3.8) are expected.

(Project for applying $\chi^2$-analysis)

We performed two kinds of $\chi^2$-fitting of the mass spectra, one with $B_0^\chi$ and the other without $B_0^\chi$, and we compare their results below. Our main interest for reanalysis in this work is to search for the possible existence of $B_0^\chi$. Accordingly, we follow the original analyses, modifying them only where they relate to this existence. We carried out the following procedures.

i) Background: In the case without $B_0^\chi$, the parameters $P_1$ through $P_6$ are determined so as to reproduce the background curve applied in the original analysis by L3, while in the case with $B_0^\chi$, the original curve is revised in the region close to threshold, where the possible effects of $B_0^\chi$ may be included.

ii) Mass and width of resonances: The values of $m_i$ and $\Gamma_i$ appearing in (3.10) are restricted in the regions given in Table IV. In this table, $M_{B_0^*}$ and $M_{B_1^*}$ are treated as free parameters, and the restrictions $M_{B_0^*} = M_{B_1^*} - 12$ MeV and $M_{B_0^*} = M_{B_1^*} - 12$ MeV are applied. Also, $\Gamma_{B_0^*}$ and $\Gamma_{B_1^*}$ are free parameters, and the restrictions $\Gamma_{B_0^*} = \Gamma_{B_1^*}$ and $\Gamma_{B_1^*} = \Gamma_{B_2^*}$ are applied. The fact that the effective mass of relevant resonances in the background processes is shifted down by $\Delta M_{\chi} = m_{B_0^*} - m_{B_1^*} = 46$ MeV is also taken into account. The upper and lower limits of the allowed regions for the free parameters $m_{B_1^*}, m_{B_2^*}, \Gamma_{B_1^*}$ and $\Gamma_{B_2^*}$ are determined in reference to their original values from L3, also listed in Table IV.

<table>
<thead>
<tr>
<th>Direct Res. Process</th>
<th>Background Res. Process</th>
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<tbody>
<tr>
<td>$B_0^\chi$</td>
<td>$B_1^*$</td>
</tr>
<tr>
<td>$m$</td>
<td>$m$</td>
</tr>
<tr>
<td>5530–5570</td>
<td>5590–5640</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>(L3; 5670 ± 10 ± 13)</td>
</tr>
<tr>
<td>$B_0^\chi$</td>
<td>$\Gamma(B_1^*)$</td>
</tr>
<tr>
<td>$m$</td>
<td>$\Gamma$</td>
</tr>
<tr>
<td>$(m(B_1^*) - 12 + 46)$</td>
<td>20–100</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>(L3; 70 ± 21 ± 25)</td>
</tr>
<tr>
<td>$B_2^\chi$</td>
<td>$B_1^*$</td>
</tr>
<tr>
<td>$m$</td>
<td>$m(B_2^*) - 12 - 46$</td>
</tr>
<tr>
<td>5730–5780</td>
<td>(L3; 5768 ± 5 ± 6)</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>$\Gamma(B_2^*)$</td>
</tr>
<tr>
<td>0–60</td>
<td>(L3; 24 ± 19 ± 24)</td>
</tr>
</tbody>
</table>

iii) Energy resolution of experiments: The effects of the energy resolution are taken into account through the relation

$$\Gamma_{R_i} = \sqrt{\Gamma_{i,\text{orig.}}^2 + \Gamma_{i,\text{resol.}}^2},$$

(3.12)

where $\Gamma_{i,\text{resol.}}$ is the energy resolution $\sigma$ of L3, $\Gamma_{R_i}$ is the value for our formula, and $\Gamma_{i,\text{orig.}}$ is the true width of the resonance $R_i$.

iv) Production couplings $r_i$: Following L3, the production ratios among resonances are assumed to be proportional to the $(2J_i + 1)$ ($J_i$ being spin of $R_i$). Then the $r_i$
are obtained from the $\Gamma_i$ through the relation
\[ r_i^2 \Gamma_i \propto (2J_i + 1). \] (3.13)

3.2. Results of analysis

The results of our analysis in cases both with and without $B_\chi^0$, are plotted in Fig. 3. The fitted curves in comparison with the data are given as follows: In the case with $B_\chi^0$ [without $B_\chi^0$] the fitted curves for exclusive data by L3, inclusive data by L3 and data by ALEPH are shown in Figs. 3(a), (c) and (e) [3(b), (d) and (f)].

The values of the mass and the width of the direct resonances, $B_\chi^0$, $B_\chi^*$ and $B_2^*$, obtained through our analysis of (a) L3 (exclusive) are given in Table V. In Table VI the values of $\chi^2$ and $\tilde{\chi}^2 (\equiv \chi^2 / \text{No. of data points} - \text{No. of param.})$ from the analysis of L3 (exclusive) are given for both of the cases with and without $B_\chi^0$. Through the inspection of the fitted curves in Fig. 3, we can conclude that our results give some evidence for the existence of $B_\chi^0$, although there is no significant improvement on the reduced $\chi^2$.

<table>
<thead>
<tr>
<th>Table V. Fitted values of mass and width (in MeV).</th>
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<tbody>
<tr>
<td>$B_\chi^0$</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>$m$</td>
</tr>
<tr>
<td>$\Gamma$</td>
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<table>
<thead>
<tr>
<th>Table VI. Values of $\chi^2$ and $\tilde{\chi}^2$.</th>
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<tbody>
<tr>
<td>with $B_\chi^0$</td>
</tr>
<tr>
<td>$\chi^2$</td>
</tr>
<tr>
<td>$\tilde{\chi}^2$</td>
</tr>
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</table>

§4. Concluding remarks

(Summary of this work) In §2 we carried out a reanalysis of the $(D^{*-} \pi^-)$ mass spectra obtained through the processes described by Eqs. (2.1) and (2.2), by applying the formulas Eqs. (2.8) and (2.9). As the intermediate resonant particles, we have taken into account $D_1^\chi$, a new chiral axial-vector meson not included in the conventional level classification scheme. As a result, we obtained possible evidence for the existence of $D_1^\chi$ with $m = 2312$ MeV and $\Gamma = 23.0$ MeV. The obtained values of the reduced $\chi^2$, $\tilde{\chi}^2 \equiv \chi^2 / (\text{No. of data points} - \text{No. of param.})$, are $\tilde{\chi}^2 = 110 / (140 - 20) = 0.923$ for the case with $D_1^\chi$ and $119 / (140 - 16) = 0.957$ for the case without $D_1^\chi$. However, the statistical accuracy of the data is very poor. It is necessary to have more accurate data in order to obtain a definite conclusion.

In §3 we have carried out a reanalysis of the $(B \pi)$ mass spectra obtained through the process Eq. (3.1), by applying the formulas (3.10) and (3.11). As the intermediate direct resonance, we have taken into account $B_0^\chi$, a new chiral scalar meson not included in the conventional level-classification scheme. As a result, we have obtained possible evidence for existence of $B_0^\chi$ with $m = 5530$ MeV and $\Gamma = 19.7$ MeV. The obtained values of the reduced $\chi^2$ are $\tilde{\chi}^2 = 18.5 / (34 - 9) = 0.74$ for the case with $B_0^\chi$ and $22.4 / (34 - 5) = 0.77$ for the case without $B_0^\chi$. However, the statistical accuracy of the data is very poor, and more accurate data are required in order to obtain a definite conclusion.

(Universal property of chiral particles) In previous works, the universal
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Fig. 3. Fitted curves in the case with [without] $B_0^X$ and experimental data of L3 (exclusive), L3 (inclusive) and ALEPH are shown, respectively, in (a), (c) and (e) [(b), (d) and (f)]. The contributions from the respective resonances are also shown.
relations\textsuperscript{10),16),17)} of chiral particles through the $D$- and $B$-meson systems were predicted from the chiral symmetry of the light quark and the heavy quark symmetry: The mass splittings of the respective chiral partners are equal, and the decay widths for the one-pion emission of the chiral particles, scalar and axial vector mesons, are also equal.

We can check some of these universal relations experimentally, using the results of the analyses given in this paper, as follows:

\begin{equation}
\Delta m_D(\equiv m(D^\chi_1) - m(D^\star)) = \Delta m_B(\equiv m(B^\chi_0) - m(B))
\end{equation}

\begin{align*}
302(2312-2010) \text{MeV} & \quad 238(=5535-5297) \text{MeV}.
\end{align*}

\begin{equation}
\Gamma(D^\chi_1 \rightarrow D^\star \pi) = \Gamma(B^\chi_0 \rightarrow B\pi)
\end{equation}

\begin{align*}
23 \text{MeV} & \quad 20 \text{MeV}.
\end{align*}

From the above, we can conclude that the theoretical predictions regarding the universal properties of chiral particles are consistent with the present experiments.

(Chiral particles $D^\chi_0$ and $B^\chi_1$) In the covariant level-classification scheme, the existence of other chiral particles, the scalar $D^\chi_0$ in the $D$-meson system and the axial-vector $B^\chi_1$ in the $B$-meson system, is also predicted. Applying the universality relations\textsuperscript{10)} Eqs. (4.1) and (4.2) they are predicted to have the masses

\begin{align*}
m(D^\chi_0) &= m(D) + \Delta m_D \approx 2170 \text{MeV}, \\
m(B^\chi_1) &= m(B^\star) + \Delta m_B \approx 5560 \text{MeV},
\end{align*}

and the widths

\begin{align*}
\Gamma(D^\chi_0 \rightarrow D\pi) &= \Gamma(B^\chi_0 \rightarrow B^\star \pi) \approx 20 \sim 25 \text{ MeV}.
\end{align*}

Presently, to our regret, there are no experimental data whose statistics are sufficiently good to allow for analysis. However, it may be worthwhile to note the possibility that the peak structure denoted as $B^\chi_0$ in Fig. 3(a) actually represents the sum of the direct $B^\chi_0$ contribution and the background $B^\chi_1$ contribution ($B^\chi_1 \rightarrow B^\star + \pi; B^\star \rightarrow B + \text{missing } \gamma$).

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References