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THE HUNT FOR THE 1^1P_1 BOUND STATE OF CHARMONIUM*

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ABSTRACT

Using the Crystal Ball detector at SPEAR, we have looked for evidence of the isospin-violating decay $\psi' \to \pi^{0\,1}P_1$, where $^1P_1$ is the predicted spin-singlet p-wave bound state of charmonium. For a $^1P_1$ state at the predicted mass (~3520 MeV), we obtain the 95% confidence level limits:

$$BR\left(\psi' \to \pi^{0\,1}P_1\right) < 0.55\%, \quad BR\left(\psi' \to \pi^{0\,1}P_1\right)BR\left({}^1P_1 \to \gamma\eta_c\right) < 0.14\% .$$

These limits are compared with simple theoretical predictions.

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With the observation of a candidate for the $2^1S_0(\eta_c')$ state of charmonium,[2) there remains only a single predicted $c\bar{c}$ bound state for which no evidence exists. This is the 1^1P_1 state, with $J^{PC} = 1^{+-}$, and a mass expected to be equal to the center-of-gravity of the $^3P_J(\chi_J)$ states, or ~3520 MeV.[3) Deviations from this mass prediction would suggest the presence of a long range spin-spin term in the quark-antiquark potential. Here, we report on a search for the $^1P_1$ state in ψ' decays using the Crystal Ball detector at the SPEAR e^+e^- storage ring.

The observation of the $^1P_1$ state in ψ' decays is complicated by the fact that both states are odd under charge conjugation, and hence, simple radiative transitions are forbidden. The most promising mechanisms appear to be transitions involving the emission of two photons: $\psi' \to \gamma\gamma{}^1P_1$. We may consider four possibilities, as illustrated in Fig. 1.

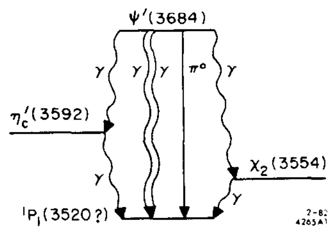

Fig. 1. Possible mechanisms contributing to the decay $\psi' \to \gamma\gamma{}^1P_1$.

(a) The decay may occur via the radiative transition to an intermediate state, the η_c', i.e., $\psi' \to \gamma\eta_c'$; $\eta_c' \to \gamma{}^1P_1$. To estimate the branching ratio for this cascade, we use the measured value for the first transition.[2) The rate for the second transition can be estimated by noting that it is an E1 transition involving the same radial wave functions as for the $\psi' \to \gamma\chi_J$ transitions, and appropriately scaling the measured rates for this process. The result is that we expect:

$$BR\left(\psi' \to \gamma\eta_c' \to \gamma\gamma{}^1P_1(3520)\right) \simeq (1\text{-}6) \times 10^{-5}\left[\frac{1\ \text{MeV}}{\Gamma_{tot}(\eta_c')}\right] \quad . \tag{1}$$

As the expected total width of the η_c' is a few MeV, this corresponds to a discouragingly small number, considering the backgrounds.

(b) Another possible intermediate state is the $\chi_2(3554)$, i.e., $\psi' \to \gamma\chi_2 \to \gamma\gamma{}^1P_1$. We may estimate the expected branching ratio for this process using the measured value for the first transition, and appropriately scaling the measured $\psi' \to \gamma\eta_c'$ (candidate) M1 transition rate for the second transition:

$$BR\left(\psi' \to \gamma\chi_2 \to \gamma\gamma{}^1P_1\right) = (0.6\text{-}4.0) \times 10^{-5}\left[\frac{1\ \text{MeV}}{\Gamma_{tot}(\chi_2)}\right] \quad . \tag{2}$$

Again, we find, with a total χ_2 width of a few MeV,[4),5) a rather small expected rate.

(c) A different possibility for $\psi' \to \gamma\gamma{}^1P_1$ decays is the direct process where two photons are radiated from the quark lines in the ψ'. Neglecting spin, we expect simply from phase space that:

$$\mathrm{BR}\left(\psi' \to \gamma\gamma\,{}^1P_1 \text{ direct}\right) < \mathrm{BR}\left(\psi' \to \gamma\gamma J/\psi \text{ direct}\right)$$
$$< 2 \times 10^{-3} \quad (90\%\ \text{C.L.}) \qquad (3)$$

where the limit is that obtained for the $\psi' \to \gamma\gamma J/\psi$ process.[4] While this limit is fairly large, the absence of a constraint on the two photons (e.g., an intermediate state, or a specific $\gamma\gamma$ mass) implies a very large background.

(d) The most promising possibility seems to be the isospin-violating decay $\psi' \to \pi^0\,{}^1P_1$, where $\pi^0 \to \gamma\gamma$. The process $\psi' \to \pi^0 J/\psi$ has been measured[6] and has been discussed by several people.[7] The currently popular idea is that this decay proceeds via $\pi^0 - \eta - \eta'$ mixing, and by an isospin-violating component in the decay amplitude. The only authors who make a prediction for the $\psi' \to \pi^0\,{}^1P_1$ decay are Segré and Weyers[7] who obtain the result: $\mathrm{BR}(\psi' \to \pi^0\,{}^1P_1) = 0.6\text{–}3.7\%$, when scaled to the expected ${}^1P_1$ mass. Unfortunately, their early paper only considered π^0–η mixing, and later authors have argued that the other contributions are important in $\psi' \to \pi^0 J/\psi$. Lacking more reliable predictions, we may attempt to remove some of the theoretical uncertainty by scaling the measured $\psi' \to \pi^0 J/\psi$ rate to the $\psi' \to \pi^0\,{}^1P_1$ process according to the formalism in Segré and Weyers:

$$\frac{\Gamma\left(\psi' \to \pi^0\,{}^1P_1\right)}{\Gamma\left(\psi' \to \pi^0 J/\psi\right)} = \frac{3}{2}\left(\frac{g_S}{g_P}\right)^2 \frac{P\left({}^1P_1\right)}{M(\psi')}\left[\frac{M(\psi')}{P(J/\psi)}\right]^3 . \qquad (4)$$

The g_S and g_P parameters refer to the amplitudes for the s-wave $(\psi' \to \pi^0\,{}^1P_1)$ and the p-wave $(\psi' \to \pi^0 J/\psi)$ processes, respectively. Segré and Weyers take $g_S = g_P$, with the cautionary remark that this is strictly an assumption. Using Eq. (4), and making the same assumption, we predict: $\mathrm{BR}(\psi' \to \pi^0\,{}^1P_1) = (1.3 \pm 0.4)\%$. This is a rather large number, and the remainder of this paper concerns the experimental search for this decay.

The Crystal Ball apparatus has been described elsewhere,[4] and only the most relevant aspects are summarized here. The detector consists primarily of a segmented array of 672 NaI(Tℓ) crystals covering 93% of 4π steradians, providing good energy $\left(\sigma_E/E = 2.6\%/E(\mathrm{GeV})^{1/4}\right)$ and angular (1–2°, energy dependent) resolution in the measurement of electromagnetically showering particles (γ and $e^\pm$). The solid angle coverage is extended to 98% with additional crystals in the endcap regions. In addition, there are spark and proportional chambers surrounding the beam pipe, providing separation of neutral and charged particles.

The ψ' data sample used in the present analysis corresponds to 1.8×10^6 produced ψ'. Events are selected with criteria[5] designed to accept hadronic ψ' decays with high efficiency (94%) and to reject backgrounds from cosmic rays, beam gas collisions, and QED processes. Tracks which are called neutral by the analysis program are selected further before being considered as photons according to the criteria given in Ref. 2 (except that photons are accepted up to $|\cos\theta| < 0.9$).

A fit (one-constraint) is made for $\pi^0 \to \gamma\gamma$ for each $\gamma\gamma$ combination in an event. Figure 2 shows the resulting inclusive energy distribution for acceptable π^0 fits. The general features of this distribution are as follows: (i) above $E_{\pi^0} \sim 600$ MeV, the minimum $\gamma\gamma$ opening angle is such that the showers from the two photons may overlap in the detector, resulting in a decreasing π^0 identification efficiency. (ii) There is a shoulder at $E_{\pi^0} \sim 540$ MeV, which corresponds to the energy expected for π^0's from the $\psi' \to \pi^0 J/\psi$ transition. However, this shoulder is contaminated by photon pairs from $\psi' \to \gamma\chi_J \to \gamma\gamma J/\psi$ decays which sometimes combine to form a (false) π^0 mass. (iii) There is an elbow in the distribution at $E_{\pi^0} \sim 430$ MeV, corresponding to the kinematic limit for $\psi' \to \pi^0\pi^0 J/\psi$ decays. (iv) The presence of structure slightly above 200 MeV may be explained in terms of contamination from $\psi' \to \gamma\chi_1$ decays, where the monochromatic γ pairs up with a low energy γ (or false gamma caused by a hadronic shower) to form an apparent π^0. (v) The interesting region, from the point of view of $^1P_1$ production, is $E_{\pi^0} \lesssim 200$ MeV. There is a rapid rise in the spectrum from threshold which is too rapid to be fit by a smooth background. However, this is apparently an artifact, as it also occurs for the J/ψ dataset. We obtain limits for the $\psi' \to \pi^0 {}^1P_1$ decay as a function of $^1P_1$ mass by fitting to an expanded version of Fig. 2 for signals in different mass regions. The resulting limits (corrected for efficiency = 0.204 ± 0.020) are shown in the second column of the table.

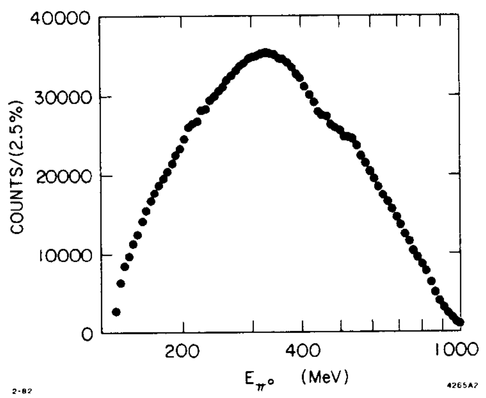

Fig. 2. Inclusive π^0 energy spectrum for ψ' decays.

Limits on $^1P_1$ production in ψ' decays

$M(^1P_1)$ (MeV)	$BR(\psi' \to \pi^0 {}^1P_1)^{a)}$ (%)	$BR(\psi' \to \pi^0 {}^1P_1 \to \pi^0\gamma\eta_c)^{a)}$ (%)
3440 - 3460	< 0.53	< 0.32
3460 - 3480	< 0.83	< 0.27
3480 - 3500	< 1.09	< 0.28
3500 - 3515	< 0.42	< 0.20
3515 - 3525	< 0.55	< 0.14
3525 - 3535	< 0.80	< 0.16
3535 - 3543	< 2.11	< 0.20

a) All numbers are 95% confidence level upper limits.

The limit at the expected $^1P_1$ mass is $BR\big(\psi' \rightarrow \pi^{0\,1}P_1(3520)\big) < 0.55\%$ (95% C.L.), which is already below our naive prediction. However, the background is fairly large, and is complicated by the presence of undesirable structure, so we have also investigated the reduction of this background by restricting our search to the process: $\psi' \rightarrow \pi^{0\,1}P_1$; $^1P_1 \rightarrow \gamma\eta_c$. We can make an estimate for the $^1P_1 \rightarrow \gamma\eta_c$ E1 transition rate by scaling the measured $\chi_J \rightarrow \gamma J/\psi$ rates (involving the same radial wave functions) appropriately: $\Gamma(^1P_1 \rightarrow \gamma\eta_c) \simeq 400\text{-}500$ keV. To estimate what branching ratio this rather large width represents, we need to know the hadronic width of the $^1P_1$ state. Lowest order QCD estimates are quite small ($\Gamma_{had} \simeq 100$ keV), but also unreliable. A better estimate may be obtained by noting that the relative widths of the $^1P_1$ and $^3P_1$ states are $\Gamma_{had}(^1P_1):\Gamma_{had}(^3P_1) = 0.83:1$ in lowest order,[8] and using experimental data to extract the $^3P_1$ hadronic width. Thus, using the measured $BR(^3P_J \rightarrow \gamma J/\psi)$ and $\Gamma_{tot}(^3P_2)$, plus the experimentally supported assumption of E1-dominance in $^3P_J \rightarrow \gamma J/\psi$ decays, we expect that $BR(^1P_1 \rightarrow \gamma\eta_c) \simeq 50\%$, or $BR(\psi' \rightarrow \pi^{0\,1}P_1 \rightarrow \pi^0\gamma\eta_c) \simeq 0.6\%$.

We have looked for this decay chain by performing kinematic fits to the hypothesis $\psi' \rightarrow \gamma\pi^0\eta_c \rightarrow \gamma\gamma\gamma\eta_c$, where the η_c is constrained in mass, but not in its decay. The resulting γ(prompt) + η_c mass distribution for acceptable fits is shown in Fig. 3. In spite of the substantial reduction in background, there is still no signal evident, so we again obtain limits by fitting to this spectrum for $^1P_1$ signals in various mass regions. The results (corrected for efficiency = 0.079 ± 0.006) are given in the table.

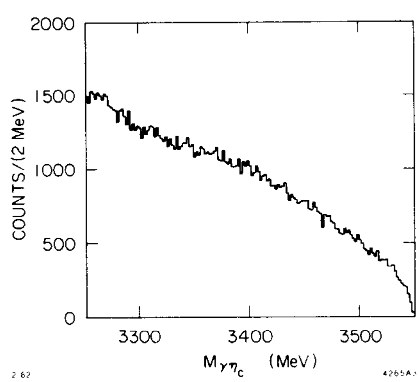

Fig. 3. $M(\gamma\eta_c)$ for events fitting the hypothesis $\psi' \rightarrow \gamma\pi^0\eta_c$.

We have found, for both our search in the inclusive π^0 spectrum and in the search for the decay chain $\psi' \rightarrow \pi^{0\,1}P_1 \rightarrow \pi^0\gamma\eta_c$, that our upper limits are below the naively expected branching ratios. There are reasons why our expectations may be in error, most notably that the assumption $g_S = g_P$ in Eq. (4) may be incorrect. In any event, further study by the theoretical community will be required to understand the result.

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