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A high resolution search for the tensor glueball candidate $\xi(2230)$

Crystal Barrel Collaboration

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Abstract

We report results of a high resolution search for the tensor glueball candidate $\xi(2230)$ in a $\bar{p}p$ formation experiment. $\pi^0\pi^0$ and $\eta\eta$ decay channels were measured in a scan of the mass region 2220 MeV to 2240 MeV. No evidence for the existence of $\xi(2230)$ was found. 95% confidence upper limits for the possible existence of ξ are presented.

As soon as the non-Abelian nature of the quark–gluon field theory, which we now call Quantum Chromodynamics (QCD), was recognized in 1972, Fritzsch and Gell-Mann [1] predicted that “there must exist glue states in hadron spectrum”, and in 1975 Fritzsch and Minkowski [2] presented a detailed discussion of the phenomenology of the spectrum of ‘glue states’, which we now call ‘glueballs’. It was pointed out that the color singlet states of two gluons should have the same quantum numbers as states of the two-photon system, i.e., $J^{PC} = 2n^{++}, (2n+1)^{++}$, and $2n^{-+}$, with $n = 0, 1, 2, \ldots$; and the order of the masses of the lowest lying states should be $0^{++}, 2^{++}, 0^{-+}, \ldots$. Since then, numerous calculations of glueball spectra have been made in various physical models [3], and they all bear out the essential features of these twenty-five year old predictions. For example, one of the most sophisticated lattice-gauge calculations (which are still made in the quenched approximation) predicts glueball masses, $M(0^{++}) \approx 1730 \pm 50 \pm 80$ MeV, $M(2^{++}) \approx 2400 \pm 25 \pm 120$ MeV [4]. Most recent experimental efforts have been directed to the search and identification of these two, the scalar and the tensor glueballs [5]. In this Letter we present the results of a high resolution search for the 2^{++} tensor glueball in a $\bar{p}p$ annihilation experiment, PS197, made with the Crystal Barrel detector [6] at the LEAR facility at CERN.

In order to provide the appropriate perspective for our choice of the method of search for the tensor glueball, it is necessary to briefly review the past searches and their conclusions.

In 1986, Mark III at SLAC, investigating radiative decays of 5.8×10^6 J/Ψ, reported [7] the observation of an abnormally narrow enhancement, dubbed ξ (now called $f_J(2220)$ by the Review of Particle Properties [8]), in the K^+K^- decay channel, with $M(\xi) = 2230 \pm 15$ MeV, and $\Gamma = 26^{+20}_{-16} \pm 17$ MeV, and in the K_SK_S channel with $M(\xi) = 2232 \pm 10$ MeV and $\Gamma = 18^{+23}_{-15} \pm 10$ MeV. They reported $J^{PC} = (\text{even})^{++}$. Upper limits at 90% confidence level were also set for $B(J/\Psi \to \gamma\xi)B(\xi \to X) < 2 \times 10^{-5}$ for $X = \pi\pi$ and $\bar{p}p$, and $< 7 \times 10^{-5}$ for $X = \eta\eta$.

Two years later, in 1988, DM2 at ORSAY reported [9] the result of their search with a sample of 8.6×10^6 J/Ψ. They failed to find any narrow enhancement, and set 95% confidence upper limits: $B(J/\Psi \to \gamma\xi)B(\xi \to X) < 2.3 \times 10^{-5}$ for $X = K^+K^-$, and $< 1.6 \times 10^{-5}$ for $X = K_SK_S$, i.e., at levels which were factor two lower than those reported for the observation by Mark III.

Three early searches for the narrow $\xi(2230)$ in the formation reactions $\bar{p}p \to K^+K^-$ and K_SK_S were also unsuccessful in finding any evidence for it [10]. Because of these negative results the existence of the narrow $\xi(2230)$ ($\Gamma < 20$–35 MeV) was considered dubious.

It should be noted that while the narrow $\xi(2230)$ was not confirmed by any other experiment prior to 1996, a broad enhancement at nearly the same mass was reported by several experiments. In the radiative decay of J/Ψ DM2 reported an enhancement in both decay channels $\xi \to K^+K^-$ and K_SK_S, with $M \approx 2200$ MeV and $\Gamma \approx 200$ MeV [9]. Studies of the peripheral reactions, $\pi^-p \to nX$ (with $X = \eta\eta'$, K_SK_S) [11], and $K^-p \to \Lambda X$ (with $X = K^+K^-$, K_SK_S) [12] also reported enhancements with nearly the same mass and width $\Gamma \approx 100$ MeV. The data were variously reported as being consistent with $J^{PC} = 2^{++}$ and 4^{++}.

In 1996, the BES detector at BEPC rekindled the interest in the narrow $\xi(2230)$ by reporting its observation in their sample of the radiative decay of 8 million J/Ψ [13]. They reported the observation of $\xi(2230)$ not only in K^+K^- and K_SK_S decay channels, but also in $\pi^+\pi^-$ and $\bar{p}p$ channels, with consistent masses and widths, $M(\xi) \approx 2232$ MeV and $\Gamma(\xi) = 15$–20 MeV.

The product ratios $B(J/\Psi \to \xi)B(\xi \to X)$ ranged from 1.5×10^{-5} to 5.6×10^{-5}. In a later publication BES reported observation of $\xi(2230)$ in the $\pi^0\pi^0$ decay channel and quoted a 95% confidence limit for $\eta\eta$ decay [14]. For the kaon, pion and $\bar{p}p$ channels the statistical significance was claimed to be between 3.6σ and 4.1σ.

The BES report of ξ decay into $\bar{p}p$ revived hopes of making a definitive observation of $\xi(2230)$ in high resolution $\bar{p}p$ formation experiments. The JETSET experiment (PS202) at LEAR (CERN) searched for $\xi(2230)$ in its K_SK_S [15] and $\Phi\Phi$ [16] decays, and failed to find any evidence for it. PS202 established 95% confidence upper limits $B(\bar{p}p \to \xi)B(\xi \to K_SK_S) < 7.5 \times 10^{-5}$ for $\Gamma(\xi) > 5$ MeV, and $B(\bar{p}p \to \xi)B(\xi \to \Phi\Phi) < 6 \times 10^{-5}$ for assumed $\Gamma = 15$ MeV. In this Letter we report the results of a search for $\xi(2230)$ by the Crystal Barrel experiment (PS197) at LEAR (CERN) in $\bar{p}p$ formation. The all neutral decay channels $\bar{p}p \to \pi^0\pi^0$, $\bar{p}p \to \eta\eta$ and $\bar{p}p \to \eta\pi^0$ were measured.

The measurements reported here were made at LEAR with the Crystal Barrel detector, which has been described in detail elsewhere [6]. Briefly, the detector, which had cylindrical geometry, consisted of an electromagnetic calorimeter of 1380 CsI crystals covering 2π azimuth and polar angles from 12° to 168°, with the useful acceptance for shower detection of 95% of 4π. The photon energy resolution was $\sigma_E/E \approx 2.5\%$ at 1 GeV, and the angular resolution was $\sigma_{\Theta,\Phi} = 1.2°$. The crystals pointed to a LH_2 target which had a length of 4.4 cm and a diameter of 1.6 cm. The detector contained elements for charged particle tracking and was surrounded by a solenoid magnet, but these were only used in the present measurements for vetoing events containing charged particles.

The antiproton beam extracted from LEAR had a momentum uncertainty of ± 0.3 MeV/c in the momentum range 1412–1461 MeV/c of the present measurements. This contributes to a $\sqrt{s}$ uncertainty of ± 0.1 MeV. The antiproton beam traversed a 100 micron beryllium foil, 150 micron mylar foils, and a 1 mm thick silicon detector, before entering the 4.4 cm long LH_2 target. This results in a mean energy loss of 1.27 MeV, and an overall, nearly uniform, $\sqrt{s}$ spread of ± 0.3 MeV.

The data for these measurements were taken with an all neutral trigger [17]. The antiproton beam was defined by the requirement of coincidence between the silicon detector immediately at the target entrance and a proportional counter, as well as anticoincidence with a scintillation veto counter behind the target. Data were taken at 9 nearly equally spaced beam momenta in the range 1412–1461 MeV/c, which corresponds to $\sqrt{s} = 2222$–2240 MeV. Between 0.5 and 1.2 million all-neutral triggers were taken at each beam momentum. The selection for $\pi^0\pi^0$, $\eta\eta$ and $\pi^0\eta$ final states was made with the following cuts: (a) no charged tracks in the Drift Chamber (b) only 4γ's, and (d) at least one pair of γ's to have invariant mass either within 135 ± 45 MeV (π^0), or 547 ± 100 MeV (η). (c) an empirically determined cut in the two-dimensional do plot of total energy E_{tot} vs. total momentum P_{tot} at $E_{\text{tot}} > 1.27P_{\text{tot}} + m_p/2 > 1800$ MeV. The result of this preselection is shown in Fig. 1 for a typical case ($P_{\text{beam}} = 1412.3$ MeV/c). In this example, 27 410 events passed these cuts out of a total of 761 000 triggers. The energy and momenta of the measured γ's, and the vertex z-position of each event were fitted to the hypotheses $\bar{p}p \to \pi^0\pi^0$, $\eta\eta$ or $\eta\pi^0$, with the confidence level set at > 5% [18]. In the example of $P_{\text{beam}} = 1412.3$ MeV/c, the following assignments resulted: $10567\pi^0\pi^0$, $407\eta\eta$ and $3571\eta\pi^0$.

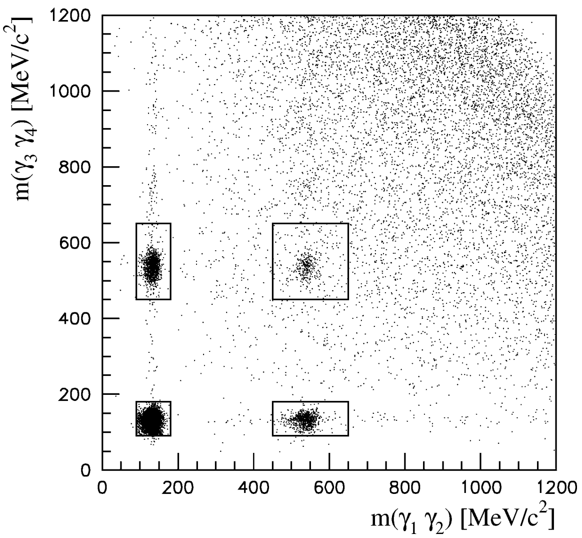

Fig. 1. Scatter plot for invariant masses $m(\gamma_1\gamma_2)$ versus $m(\gamma_3\gamma_4)$ at 1412.3 MeV/c^2. There are three entries per event. The $\pi^0\pi^0$ and $\eta\eta$ events are visible in the boxes on the diagonal, as are the $\eta\pi^0$ events in the off-diagonal boxes.

The overall acceptance and efficiency for event selection was estimated by Monte Carlo simulation to be 33% for $\pi^0\pi^0$, 36% for $\eta\eta$ and 35% for $\eta\pi^0$. Monte Carlo simulations also show that there was no significant contamination in $\pi^0\pi^0$ event selection. The $\eta\eta$ selection is estimated to have $\approx (0.5 \pm 0.2)$% misidentified $\eta\pi^0$, and (2.8 ± 0.4)% misidentified $\pi^0\pi^0$. The $\eta\pi^0$ selection has (0.05 ± 0.02)% misidentified $\eta\eta$, and no $\pi^0\pi^0$.

The observed number of counts $N(X)$ in a decay channel X is related to the cross section $\sigma(X)$ as

$$N(X) = N(\bar{p}) \cdot N(\text{target}) \cdot \sigma(X) \cdot \epsilon(X),$$

where $\epsilon(X)$ is the efficiency for the detection of the final state X including geometrical acceptance. From the known length and density of the LH_2 target, $(1/N(\text{target})) = 5.33 \times 10^6$ µb. The number of incident $\bar{p}$ is determined by the coincidence of signals in the beam defining proportional counter at the exit of the LEAR $\bar{p}$ extraction channel and the central silicon detector at the entrance of the LH_2 target. Account is taken of the detector live-time and pile-up. The corrections for pile-up varied from 5% to 9% from point to point. A detailed discussion of the procedure used for absolute cross section determination is presented elsewhere [19]. Both the differential cross sections and the integrated cross sections in the range $\cos\theta = 0$ to 0.85 are determined for $\pi^0\pi^0$, $\eta\eta$ and $\eta\pi^0$ final states. The statistical errors in cross sections are, on average, 1.7%, 6.5% and 2.8% for $\pi^0\pi^0$, $\eta\eta$ and $\eta\pi^0$, respectively. We estimate that the additional uncertainty in our overall absolute cross section normalization is $< \pm 10$%. We note that the absolute cross section for $\bar{p}p \to \pi^0\pi^0$ in our energy region are approximately a factor two larger than reported by Dulude et al. [20], and in agreement with similar findings of Anisovich et al. [21].

The cross sections integrated in the region $\cos\Theta_{\text{cm}} = 0$–0.85 for $\bar{p}p \to \pi^0\pi^0$, $\eta\eta$ and $\eta\pi^0$ are shown in Fig. 2, and listed in Table 1.

In the small region of $\sqrt{s}$ investigated in our measurements, in absence of a resonance, the cross sections can be reasonably fitted with straight lines. These straight line fits to the cross sections, $\sigma = A + B(\sqrt{s} - 2200)$, are shown in Fig. 2. The results are,

$$\begin{aligned}
\pi^0\pi^0:\quad & A = 47.2 \pm 1.1\ \mu\text{b},\\
& B = -0.229 \pm 0.036\ \mu\text{b},\\
& \chi^2/\text{dof} = 1.37,\\
\eta\eta:\quad & A = 10.1 \pm 1.1\ \mu\text{b},\\
& B = -0.041 \pm 0.033\ \mu\text{b},\\
& \chi^2/\text{dof} = 0.68,\\
\eta\pi^0:\quad & A = 39.0 \pm 1.8\ \mu\text{b},\\
& B = -0.144 \pm 0.057\ \mu\text{b},\\
& \chi^2/\text{dof} = 0.34.
\end{aligned}$$

These fits are found to be consistent with the cross section measured by us at 1512 MeV/c and 1640 MeV/c [19]. Fig. 2 shows that in none of the integrated cross sections there is any indication of structure. Since the $\eta\pi^0$ decay channel, with isospin 1, cannot have an $I = 0$ glueball, we can remove all luminosity uncertainties by considering $\sigma(\pi^0\pi^0)/\sigma(\pi^0\eta)$ and $\sigma(\eta\eta)/\sigma(\pi^0\eta)$. These are also shown in the bottom two panels of Fig. 2. In both cases essentially perfect fits to straight line are obtained with $\chi^2 = 0.31$, and 0.50, respectively. To summarize, there is no evidence in our integrated cross section data for any structure.

In order to put quantitative limits for the possible presence of a resonance in these data, we have made the following analysis of the $\pi^0\pi^0$ and $\eta\eta$ integrated cross sections. The measured cross sections are considered as the sum of a linear background plus a $J = 2$ Breit–Wigner resonance of the familiar form,

$$\sigma_{\text{obs}}^X = \left(A + B\sqrt{s}\right) + \sigma_0 \frac{B_{\text{in}} B_{\text{out}}}{1 + [2[\sqrt{s} - M_R]/\Gamma]^2},$$

where the peak cross section for the Breit–Wigner resonance

$$\sigma_0 = (2J+1)\left(\frac{4\pi(\hbar c)^2}{s - 4m_p^2}\right) \approx (0.17 - 0.16)\ \mu\text{b} \times 10^5$$

in our scan region for a $J = 2$ resonance. A minimum χ^2 (maximum likelihood) fit is done with A, B, M_R and Γ_R fixed and $B_{\text{in}} B_{\text{out}}$ allowed to vary freely. A and B are fixed at the values determined in the fits described above. Two fixed values of width, $\Gamma =$ 10 MeV and 20 MeV, are used and M_R is varied in small steps from 2222 to 2240 MeV. In this manner 95% confidence upper limits, shown in Fig. 3 are obtained. We note that these imply that for Γ_R between

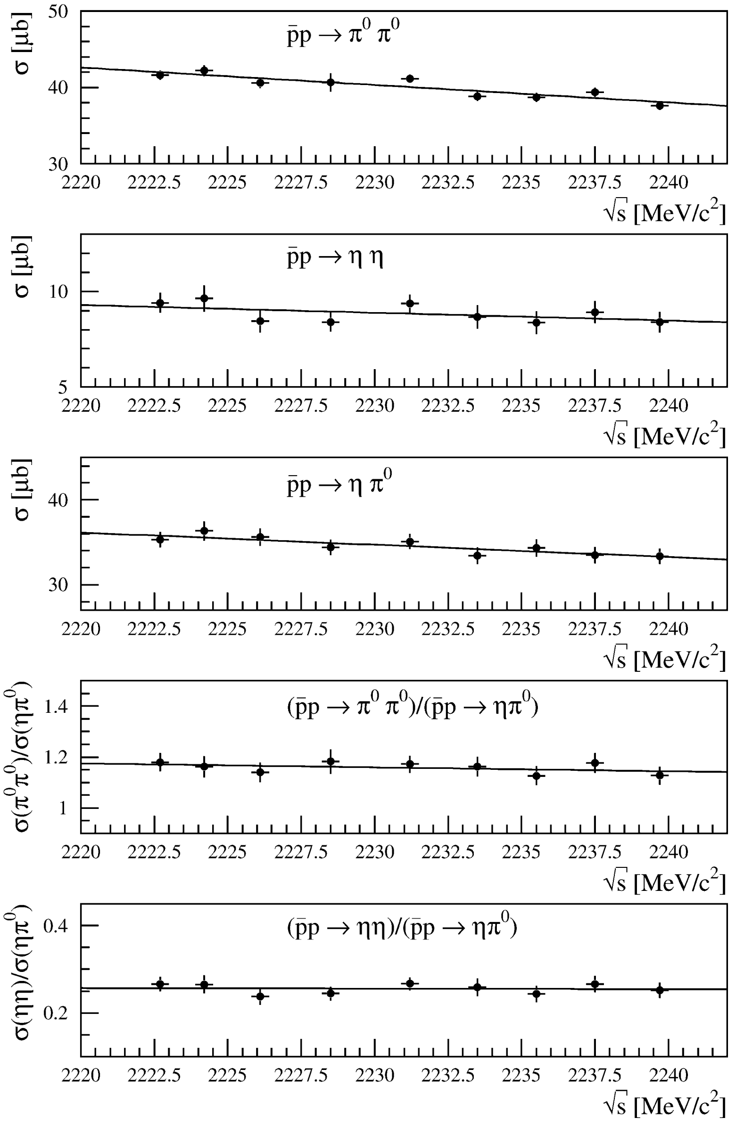

Fig. 2. The upper three panels show measured cross sections integrated in the region $0 < \cos\theta \leqslant 0.85$ for $\bar{p}p \to \pi^0\pi^0$, $\eta\eta$, and $\eta\pi^0$, and the straight line fits through them. The lower two panels show $\pi^0\pi^0$ and $\eta\eta$ cross sections divided point by point by the $\eta\pi^0$ cross sections. In all cases, only the statistical errors are shown.

10 and 20 MeV,

$$B(\bar{p}p \to \xi)B\left(\xi \to \pi^0\pi^0\right) < 6 \times 10^{-5}, \quad 95\% \text{ CL.} \tag{1}$$

$$B(\bar{p}p \to \xi)B(\xi \to \eta\eta) < 4 \times 10^{-5}, \quad 95\% \text{ CL.} \tag{2}$$

As mentioned earlier, differential cross sections for all three reactions were also measured. An example of the angular distribution for $\pi^0\pi^0$ at $\sqrt{s} = 2222.7$ MeV, is presented in Fig. 4. Also shown in Fig. 4 is the angular distribution for $\eta\eta$, averaged over $\sqrt{s} = 2222.7$–2239.7 MeV, in order to improve statistics. A simple analysis of the differential cross sections in terms of Legendre polynomials was made for both $\pi^0\pi^0$ and $\eta\eta$. It was found that the coefficients up to the order of 8 were required, and they all showed

Table 1
Antiproton beam momenta, center of mass energies and cross sections integrated in the region of $0 < \cos\theta \leqslant 0.85$ for the reactions $\bar{p}p \to \pi^0\pi^0$, $\eta\eta$ and $\eta\pi^0$. Only statistical errors are listed for the cross sections

$P_{\bar{p}}$ (MeV/c)	$\sqrt{s}$ (MeV)	Integrated cross section		
		$\bar{p}p \to \pi^0\pi^0$ (μb)	$\bar{p}p \to \eta\eta$ (μb)	$\bar{p}p \to \eta\pi^0$ (μb)
1412.3	2222.6 ± 0.3	41.6 ± 0.6	9.4 ± 0.5	35.3 ± 0.9
1416.4	2224.1 ± 0.3	42.2 ± 0.7	9.6 ± 0.7	36.3 ± 1.1
1422.0	2226.1 ± 0.3	40.6 ± 0.7	8.4 ± 0.6	35.6 ± 1.0
1428.7	2228.4 ± 0.3	40.7 ± 1.2	8.4 ± 0.5	34.4 ± 0.9
1436.4	2231.1 ± 0.3	41.1 ± 0.6	9.4 ± 0.5	35.1 ± 0.9
1443.1	2233.4 ± 0.3	38.8 ± 0.6	8.7 ± 0.6	33.4 ± 1.0
1448.7	2235.5 ± 0.3	38.7 ± 0.6	8.4 ± 0.6	34.3 ± 1.0
1454.3	2237.4 ± 0.3	39.4 ± 0.6	8.9 ± 0.6	33.5 ± 1.0
1460.5	2239.6 ± 0.3	37.6 ± 0.6	8.4 ± 0.5	33.4 ± 0.9

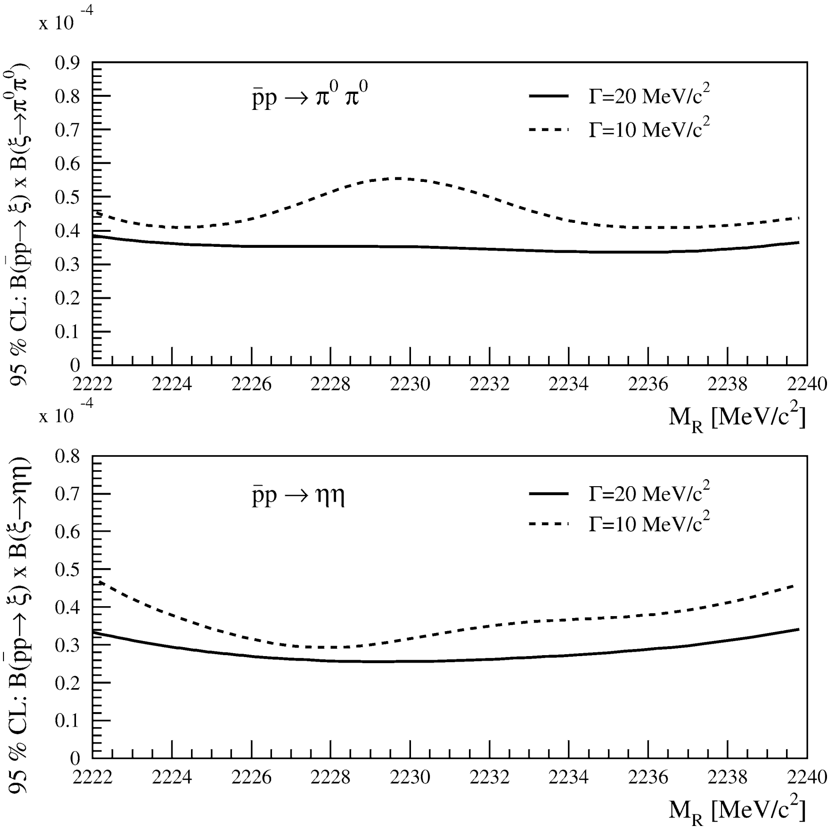

Fig. 3. 95% confidence upper limits for the product branching ratios, $B(\bar{p}p \to \xi)B(\xi \to \pi^0\pi^0)$, and $B(\bar{p}p \to \xi)B(\xi \to \eta\eta)$, as function of assumed mass of ξ. Two different values of width of ξ, $\Gamma(\xi) = 10$, and 20 MeV were assumed.

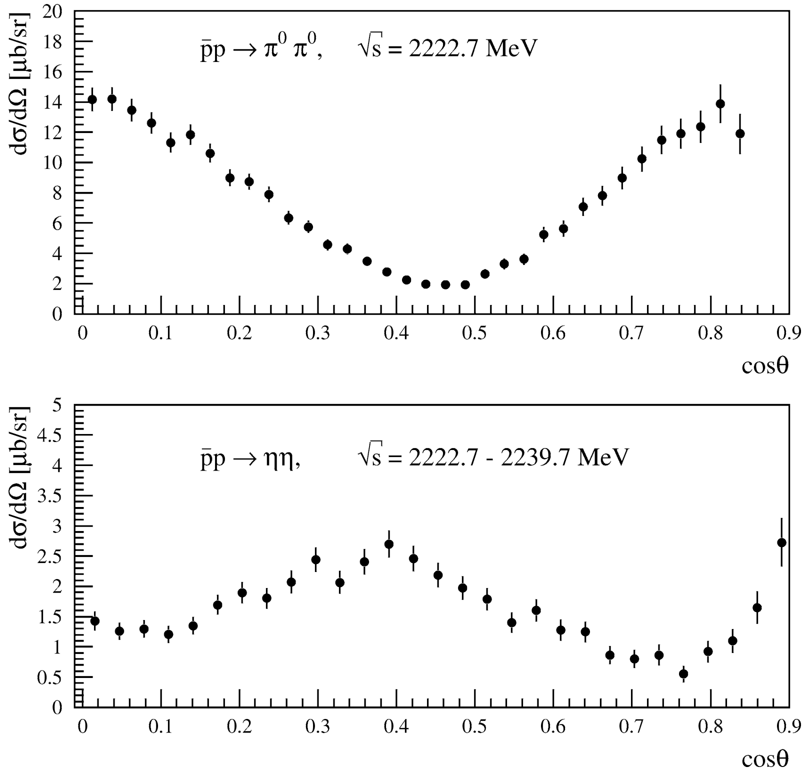

Fig. 4. Illustrating measured differential cross sections for $\bar{p}p \to \pi^0\pi^0$ and $\bar{p}p \to \eta\eta$. For $\eta\eta$, cross sections at four energy points $\sqrt{s} = 2222.7$–2239.7 MeV were averaged in order to reduce statistical scatter.

smooth evolution from $\sqrt{s} = 2222$ to 2240 MeV. No indication of any behavior indicative of a resonance was found.

Our measured product branching ratio can be combined with the branching ratios reported by BES to yield some other limits. For example,

$$
\begin{aligned}
&B(J/\Psi \to \gamma\xi) \\
&\quad = \big[\big\{B(J/\Psi \to \gamma\xi)B(\xi \to \bar{p}p)\big\} \\
&\qquad \times \big\{B(J/\Psi \to \gamma\xi)B\big(\xi \to \pi^0\pi^0\big)\big\}\big]^{1/2}_{\mathrm{BES}} \\
&\qquad \times \big[B(\xi \to \bar{p}p)B\big(\xi \to \pi^0\pi^0\big)\big]^{-1/2}_{\mathrm{CB}}
\end{aligned}
$$

leads to

$$B(J/\Psi \to \gamma\xi) > 0.29\%, \quad 95\%\ \mathrm{CL}, \tag{3}$$

which would be comparable to the largest measured radiative widths of J/Ψ. (For the BES product branching ratio for $\pi^0\pi^0$ we actually use the weighted average of their product branching ratios for $B(\pi^+\pi^-)$ and $B(\pi^0\pi^0)$).

Upper limits can also be derived by using the above result in the other product branching ratios reported by BES. These are 0.51%, 1.6%, 1.9%, 1.1% and 0.9% (95% confidence) for the branching ratios for $\xi \to \bar{p}p$, $\pi^0\pi^0$, $\pi^+\pi^-$, K^+K^- and K_SK_S, respectively.

To summarize the results of our measurements of $\bar{p}p \to \pi^0\pi^0$ and $\eta\eta$, we find no evidence for the existence of the narrow glueball candidate $\xi(2230)$ (or $f_J(2220)$) anywhere in the mass range 2222 to 2240 MeV. We have established 95% confidence upper limits for the product branching ratios of 6×10^{-5} and 4×10^{-5} for the formation of $\xi(2230)$ in $\bar{p}p$ annihilation and its decay into $\pi^0\pi^0$ or $\eta\eta$, respectively. We are led to conclude that either the narrow $\xi(2230)$ does not exist in the mass range of our scan, or, if the BES branching ratio results are correct, its coupling to the $\bar{p}p$ channel is very weak.

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