FORMATION OF THE χ_1 AND χ_2 CHARMONIUM RESONANCES IN ANTIPROTON–PROTON ANNIHILATION AND MEASUREMENTS OF THEIR MASSES AND TOTAL WIDTHS

R704 Collaboration

Annecy (LAPP)–CERN–Genoa–Lyon (IPN)–Oslo–Rome–Strasbourg–Turin

C. BAGLIN [a], S. BAIRD [b], G. BASSOMPIERRE [a], G. BORREANI [c], J.-C. BRIENT [a], C. BROLL [a,1], J.-M. BROM [d], L. BUGGE [e], T. BURAN [e], J.-P. BURQ [f], A. BUSSIÈRE [a], A. BUZZO [g], R. CESTER [c], M. CHEMARIN [f], M. CHEVALLIER [f], B. ESCOUBES [d], J. FAY [f], S. FERRONI [g], V. GRACCO [g], J.-P. GUILLAUD [a], E. KHAN-ARONSEN [b], K. KIRSEBOM [e], A. KYLLING [e], B. ILLE [f], M. LAMBERT [f], L. LEISTAM [b], A. LUNDBY [b], M. MACRI [g], F. MARCHETTO [c], E. MENICHETTI [c], Ch. MÖRCH [a], B. MOUELLIC [b], D. OLSEN [e], N. PASTRONE [c], L. PETRILLO [h], M.G. PIA [g], J. POOLE [b], M. POULET [a], G. RINAUDO [c], A. SANTRONI [g], M. SEVERI [h], G. SKJEVLING [e] and B. STUGU [e]

[a] *LAPP, F-74019 Annecy-le-Vieux Cedex, France*
[b] *CERN, CH-1211 Geneva 23, Switzerland*
[c] *University of Turin, I-10124 Turin, Italy*
[d] *CRN, F-67037 Strasbourg Cedex, France*
[e] *University of Oslo, N-1000 Oslo 3, Norway*
[f] *IPN Lyon, F-69622 Villeurbanne, France*
[g] *University and INFN, I-16126 Genoa, Italy*
[h] *University of Rome, I-00100 Rome, Italy*

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In an experiment performed at the CERN-ISR the direct formation is observed of the χ_1 and χ_2 charmonium states in proton–antiproton annihiliation. A novel technique provided excellent energy resolution together with small background and reduced systematics. The following values for the masses and total widths of the states were obtained: $\Gamma_{\chi_1} < 1.3$ MeV (95% CL); $m_{\chi_1} = (3511.3 \pm 0.4 \pm 0.4)$ MeV; $\Gamma_{\chi_2} = (2.6 + 1.4 - 1.0)$ MeV; $m_{\chi_2} = (3556.9 \pm 0.4 \pm 0.5)$ MeV. First measurements of the partial widths to antiproton–proton are also reported: $\Gamma(\chi_1 \to \bar{p}p) = 57^{+13}_{-11} \pm 11)$ eV and $\Gamma(\chi_2 \to \bar{p}p) = (233^{+51}_{-45} \pm 48)$ eV.

1. Introduction. The study of the charmonium spectroscopy has attracted, in the years following the discovery of the J/ψ resonance, considerable attention both on the theoretical and on the experimental side.

Most of the available information on the ^3P states (χ states) of the charmonium system came from experiments at e^+e^- storage rings where the radiative decays of the ψ' resonance have been studied. The previous determinations [1] of χ masses and total widths were derived from energy measurements of the photons in the reaction:

$$e^+e^- \to \psi' \to \chi + \gamma .$$

However, in spite of the large statistics and of refined electromagnetic calorimetry the total width measurements were limited by the detector energy resolution ($\Delta E_{\mathrm{FWHM}} \sim 12$ MeV), while the mass measurements suffered from a ±4 MeV absolute calibration uncertainty.

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We report results on new measurements done on the χ_1 ($^3P_1$) and χ_2 ($^3P_2$) states in an experiment performed at the CERN ISR to investigate the properties of the charmonium states formed in $\bar{p}p$ annihilations. Since the $\bar{p}p$ system couples directly to any charmonium state (unlike e^+e^- which couples only to $J^{PC} = 1^{--}$ states), these states can be formed directly and a detailed scan around the resonance peak energy can be done to provide a measurement of the mass and of the total width independent of the energy resolution of the detector.

The strength of the method relies on the excellent energy definition of the initial state achieved in this experiment with antiproton cooling techniques and the use of a jet target [‡1].

2. Experimental set up. Here we only sketch the features of the method and of the apparatus that are most important for this analysis. A detailed description of the experimental technique and of the performance of the apparatus are reported elsewhere [3]. The antiproton–proton annihilations were produced by intersecting an antiproton beam coasting in ring 2 of the ISR with a molecular hydrogen jet at an angle of 90° to the beam. The resulting interaction volume was $0.8 \times 0.6 \times 0.9$ cm^3 ($w \times h \times l$, 90% containment). Momentum cooling was applied to the antiproton beam such that a momentum spread of $dp/p = {}^{+4.5}_{-9} \times 10^{-4}$ (RMS) was achieved, corresponding to ${}^{+0.70}_{-1.4}$ MeV CM energy spread at the χ resonances.

The average luminosity was $\sim 1.5 \times 10^{30}$ cm^{-2} $\times$ s^{-1}, obtained with 5×10^{10} circulating antiprotons and a jet thickness of 10^{14} atoms/cm^2.

The detector was a non-magnetic two arm spectrometer designed to select the electromagnetic final states e^+e^-, $e^+e^-\gamma$, $\gamma\gamma$. This choice was made in order to suppress the huge non-resonant hadronic background ($\sigma_{tot} > 10^6 \sigma_{\bar{c}c}$) coming from $\bar{p}p$ collisions.

The two arms were placed symmetrically with respect to the $\bar{p}$ beam and covered each 45 degrees in azimuthal and 17 to 66 degrees in polar angle. They were equipped with a front scintillator (S), scintillator hodoscopes and MWPC's for charged particle tracking, a freon Cherenkov counter (C) for electron identification and electromagnetic calorimeters to measure the energy of electron or γ induced showers and designed to give good $e^\pm/\pi^\pm$ and γ/π^0 separation. Each calorimeter was longitudinally subdivided in three parts: a lead scintillator sandwich (5 X_0) with θ and φ segmentation (precalorimeter, $\simeq 3°$ granularity), four x–y planes of proportional chambers with analogue strip readout and a lead glass array (10 X_0).

The two arms were complemented by 50 guard counters of various sizes which consisted of (a) scintillation counters followed by (b) lead and scintillator sandwiches (4.6 X_0) covering the full azimuth and 1.8 to 77 degrees in the polar angle. They were used as veto for charged or neutral particles or, alternatively, to detect photons outside the two detector arms and provide a rough determination of the shower center of gravity.

A silicon detector telescope was used to monitor the luminosity by measurements of the recoil protons from forward $\bar{p}p$ elastic scattering (±5% precision).

During spring 1984 we collected data on the reaction $\bar{p}p \to e^+e^-$ + anything scanning around the energy of formation of the χ_1 and χ_2 resonances and near the centre-of-gravity of the χ states. Integrated luminosities of 494 nb^{-1} (χ_1), 763 nb^{-1} (χ_2) and 1019 nb^{-1} (centre-of-gravity) were accumulated.

At the beginning of each period of data taking the beam calibration was checked [3]. The absolute centre-of-mass energy value was then known at any time to within $\pm 1.2 \times 10^{-4}$ (relative error).

3. Selection of events. χ formation was detected in our apparatus through the process

$$\bar{p}p \to \chi \to J/\psi + \gamma\,, \quad J/\psi \to e^+e^-\,. \tag{1}$$

The trigger was devised to accept inclusive J/ψ production requiring one electron candidate per arm. The dominant component of candidates in the electron samples were due to e^+e^- pairs originating from π^0 Dalitz decays or from ordinary π^0 decays with one photon converted in the wall of the ISR vacuum pipe (0.03 X_0), or to charged pions producing a delta ray in the Cherenkov counter. The first background would manifest itself with the characteristics of two superimposed electron tracks (i.e. large signals in S and C), the second would exhibit an anomalous longitudinal shower development. In the off-line analysis a preliminary selection accepted only tracks pointing back to the interaction region and in line with an

‡1 The use of the CERN Intersecting Storage Ring for charmonium studies was first proposed by Dalpiaz [2].

electromagnetic shower in the calorimeter, 416 and 541 events were thus selected respectively at the χ_1 and χ_2 energy. The invariant mass was calculated from the measured directions and energies. When more than one track was present in one arm, the highest combination was retained. The distribution obtained is shown in fig. 1. The inset in fig. 1a shows the equivalent distribution for the data taken at the J/ψ formation energy. Based on our understanding of the background components, we applied to this event sample a set of cuts designed to sharpen the electron definitions.

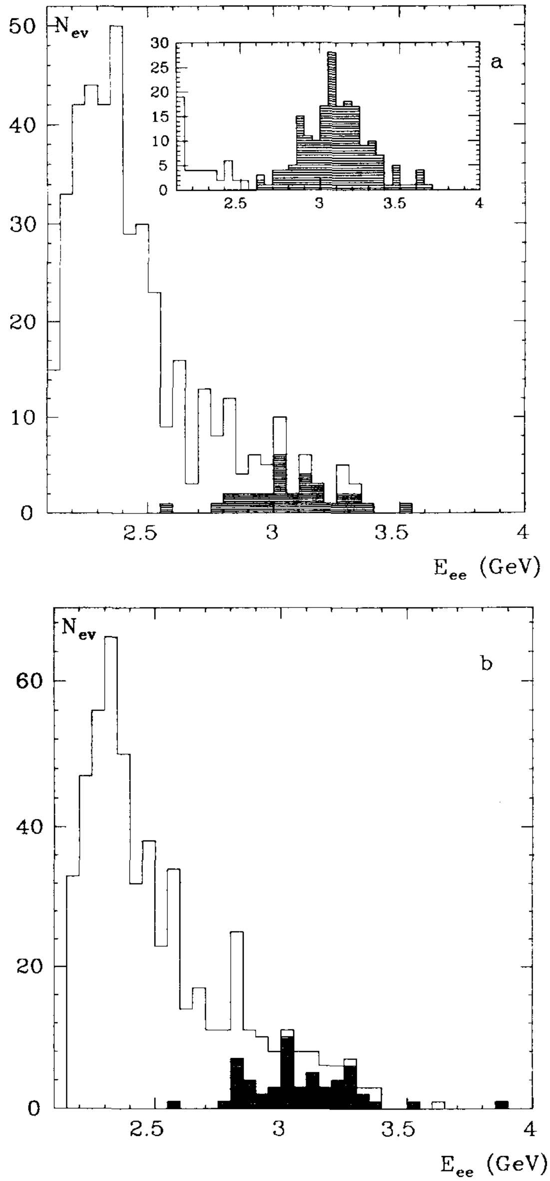

Fig. 1. The invariant mass of the electron pairs: (a) χ_1 energy region; (b) χ_2 energy region. The thin line histograms refer to uncut samples and the shaded histograms to the final selection. The inset shows the same for J/ψ formation events.

Tracks were rejected if:

(a) The digitized signals from the front scintillator (S) and from the Cherenkov counter were both above a threshold value corresponding to 1.8 minimum ionizing particles (mip) equivalent in S and 1.8 times the average electron signal in the Cherenkov counter.

(b) The energy release in the precalorimeter was $\leqslant$100 MeV (equivalent to the release from 2.5 mip's).

The efficiency of the cuts was determined from a clean sample of $\bar{p}p \to J/\psi \to e^+e^-$ events [3] to be 0.93 ± 0.02.

In the final step of the analysis we asked the topology and kinematics of the event to be compatible with the formation-decay chain (1). From the measured electron directions we reconstructed the direction of emission of the photon radiated in the χ decay (two kinematical solutions) and searched for evidence of energy depositions in the detector elements (arm calorimeters or guard counters), if any, along the possible pathways of the photon. Events were rejected either when this correspondence between photon direction and detector response was not found or when energy clusters other than those expected from the three-body final state were observed anywhere in the detectors.

After this we produce the outstanding J/ψ signal seen as the shaded histograms in fig. 1. The widths of the J/ψ peaks agree with the experimental resolution. We note that none of the selection criteria is correlated to the e^+e^- mass, so that the appearence of a prominent peak around the J/ψ mass gives us confidence that indeed we are in the presence of J/ψ production. We are left with 30 (50) events that we ascribe to χ_1 (χ_2) formation through process (1). However, background from the non-resonant process

$$\bar{p}p \to J/\psi\pi^0 \to J/\psi\gamma\gamma \qquad (2)$$

could still be present, due to the poor π^0/γ separation of the guard counters. The background was measured from data taken during the $^1P_1$ scan (at the CM energy 3520–3530 MeV) [4]. Subject to the same selection of the present χ samples, these data contained no event in an integrated luminosity of 309 nb^{-1} [‡2]. The upper limit (84% CL) for the background cross section, once corrected for geometrical and selection losses is <65 pb, very small compared to measured peak cross sections exceeding 1 nb for both χ_1 and χ_2.

4. Results. Fig. 2 shows the measured cross sections for process (1), versus the CM energy. Horizontal bars represent the RMS uncertainty corresponding to the beam momentum dispersion. Qualitatively, one may notice that the width of the χ_1 resonance is compatible with the instrumental width due to the beam momentum dispersion, while the χ_2 width appears to be larger.

To extract the χ widths, masses and coupling to $\bar{p}p$ we perform, separately for the χ_1 and χ_2, a maximum likelihood analysis.

[‡2] This excluded data taken at the χ's centre of gravity. There, in 710 nb^{-1} luminosity, we found two events fitting both reaction (1) and (2); however, they also belong to the sample of five $^1P_1$ candidates discussed in ref. [4]. Even if we considered them as background, the corresponding cross section would be $\sigma_{bkg} = (22^{+28}_{-14})$ pb, indeed very small. Both background estimates were tried in the analysis of the χ parameters, leading to substantially identical results.

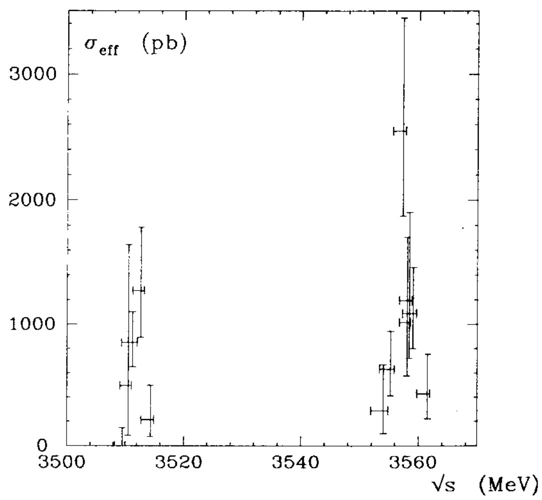

Fig. 2. The measured cross sections for $\bar{p}p \to J/\psi + \gamma$ versus CM energy. Horizontal bars represent RMS energy spread as measured by the Schottky noise method [3]. The cross sections have been corrected for geometrical and selection inefficiencies.

The likelihood function is written as:

$$\mathcal{L} = \prod_{i=1,N} m_i^{n_i} \exp(-m_i)/n_i! ,$$

n_i is the observed number of events for each of the N energy settings, m_i is the expected number of events given by:

$$m_i = L_i \epsilon_i \left(\int f_i(E)\, \mathrm{BW}(E)\, \mathrm{d}E + \sigma_{bkg} \right) ,$$

where L_i is the integrated luminosity; ϵ_i the overall efficiency = 0.099 (0.075) for χ_1 (χ_2); σ_{bkg} a non-resonant background cross section assumed to be constant with energy; $f_i(E)$ the beam profile function normalized to 1; BW(E), the Breit–Wigner cross section, a function of the resonance parameters m, Γ, $\Gamma_{\bar{p}p}$ and of the known product b = BR ($\chi \to J/\psi\gamma$) × BR ($J/\psi \to e^+e^-$), that we inferred from published data [1,5].

By maximizing log $\mathcal{L}$, we determine m, Γ, the product $\Gamma_{\bar{p}p} b$ and σ_{bkg}.

The geometrical acceptance was calculated by Monte Carlo methods, while the combined detector and selection efficiency was measured on J/ψ formation events [3] by submitting them to the same selection criteria as applied to the χ samples. The data taken in the $^1P_1$ scan have been used to constrain the background in both the χ_1 and χ_2 fits.

The results are summarized in table 1.

Likelihood contours in the variables BR ($\bar{p}p$ branching ratio) versus Γ with m and b fixed are shown in fig. 3. The strong correlation exhibited reflects the fact that for a narrow resonance all the information comes from the event rate, which measures directly the partial width to $\bar{p}p$. Notice that the correlation is less pronounced for the χ_2 since, for a relatively wide resonance, the resolving power of the beam is large enough to permit a direct measurement of the resonance shape. The systematic uncertainty from b and our normalization allows a ±23% shift of the contours along the ordinate (BR), but does not affect Γ.

We notice that our data plus an independent measurement of the $\bar{p}p$ branching ratio of the χ_1 would set tight bounds on the total width. For the χ_1 a lower limit on the total width around 100 keV can already be set from the limit on the branching ratio BR $< 4.3 \times 10^{-4}$ measured by Mark II [6].

Table 1
Results of the maximum likelihood fits. All errors are standard deviations except when only a limit is given, in which case the limit is given at 95% confidence level. Systematic errors on m reflect the uncertainty in the absolute beam momentum calibration. Errors in $\Gamma_{\bar{p}p} \cdot b$ include the statistical as well as the normalization uncertainty. The second errors given to $\Gamma_{\bar{p}p}$ and to the branching ratio come from the uncertainty in b. We used for b the following values: $b(\chi_1) = 0.0207 \pm 0.0040$ and $b(\chi_2) = 0.0092 \pm 0.0019$.

State	Events	m (MeV)	Γ (MeV)	$\Gamma_{p\bar{p}} \times b$ (eV)	$\Gamma_{\bar{p}p}$ (eV)	$BR(\chi \to \bar{p}p) \times 10^{-4}$
χ_1	30	$3511.3 \pm 0.4 \pm 0.4$	<1.3	$1.18^{+0.26}_{-0.24}$	$57^{+13}_{-11} \pm 11$	>0.54
χ_2	50	$3556.9 \pm 0.4 \pm 0.5$	$2.6^{+1.4}_{-1.0}$	$2.14^{+0.47}_{-0.41}$	$233^{+51}_{-45} \pm 48$	$0.90^{+0.41}_{-0.26} \pm 0.19$

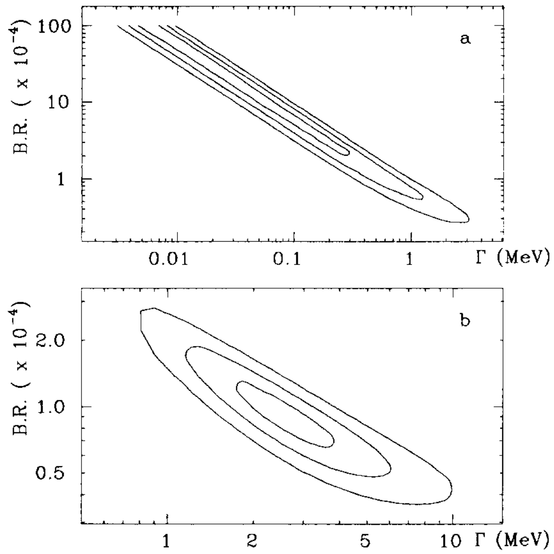

Fig. 3. Maximum likelihood contours in the variables Γ versus BR (a) χ_1 resonance; (b) χ_2 resonance. The lines correspond to 1, 2, 3 standard deviations in the gaussian limit.

5. Comments. The results were checked against systematic errors arising from:

(1) The binning in energy in the likelihood analysis.

(2) The parametrization of the beam profiles.

(3) A systematic relative shift of ± 1 MeV/c in the beam calibration during different weeks of running (this only applies to the χ_2 where the data were collected in two weeks).

All the above effects resulted in changes in the best fit widths or branching ratios $<5\%$, entirely negligible compared to the statistical errors. Point (3) was found to produce a ± 0.2 MeV shift of the χ_2 mass, that we incorporated in the systematic error.

6. Conclusions. The use of a cooled antiproton beam impinging on a H_2 jet target has proved to be an excellent technique for measuring the characteristics of $\bar{c}c$ states formed from $\bar{p}p$ annihilations. The only limitations came from the limited number of antiprotons and machine time. In a small statistics experiment we confirm previous measurements of the χ_1 and χ_2 masses with a tenfold reduction of the systematic errors, and we obtain the first measurements of their partial widths, into the $\bar{p}p$ final state. We place tighter bounds on the total widths, in particular we find that the total width of the χ_1 is definitely smaller than that of the χ_2 resonance, as suggested by gluon counting arguments ‡3.

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‡3 See e.g. ref. [7]. Barbieri, Gatto and Remiddi [8] calculated the ratio of the hadronic widths of the χ_0, χ_1 and χ_2 states in perturbative QCD.

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