# **Charmonium Radiative Decays**

- Total widths from E760/E835
- BR's from Crystal Ball
- M2,E3 terms: Angular Distributions
- From  $O(\beta^2)$  to  $O(\beta^4)$
- Future challenges: CLEO–C

# **Selection Rules and Naming Schemes**

C-Parity conservation implies C<sub>f</sub>=-C<sub>f</sub>:

Parity Flip and Electric/Magnetic multipoles

$$rac{}{}_{\sim} e.g.: J/\psi \rightarrow \gamma \eta_{c}$$





Roberto Mussa, Genoa Workshop on Charmonium, June 8,2001

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#### CHARMONIUM SPECTROSCOPY





SPECTROSCOPY

**CHARMONIUM** 



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## **Non Relativistic Partial Widths**

- Electric dipole transitions:
- $\searrow \Gamma(X_c \to \gamma J/\psi) = |EI|^2 (1 + O(\beta^2)) = \frac{4}{9} e_c^2 \alpha E_{\gamma}^3 \langle r_{if} \rangle^2$
- $> \Gamma(\psi' \to \gamma X_{cJ}) = |EI|^2 (1 + O(\beta^2)) = \frac{2J + 1}{3} \frac{4}{9} e_c^2 \alpha E_\gamma^3 \langle r_{if} \rangle^2$ 
  - Magnetic dipole transitions

$$\sum \Gamma(J/\psi \to \gamma \eta_c) = |MI|^2 = \frac{4}{9} e_c^2 \alpha \frac{E_y^3}{m_c^2} \frac{1}{1 + E_y/\sqrt{M_f^2 + E_y^2}} |I_{if}|^2$$

## Radiative widths: experimental overview

All current values are obtained combining e<sup>+</sup>e<sup>-</sup> and p<sup>®</sup> data as follows:

$$\Gamma_{rad}(\Psi_i \to \gamma \Psi_f) = \Gamma_{tot}(\Psi_i) * BR(\Psi_i \to \gamma \Psi_f)$$

• The fractional error is given by:  $\frac{o_I}{r}$ 

y: 
$$\frac{\delta \Gamma_{tot}}{\Gamma_{tot}} \oplus \frac{\delta BR}{BR} = \frac{\delta \Gamma_{rad}}{\Gamma_{rad}}$$

r

The current values (PDG 2000) are summarized below:

Transition	Rad. Width (keV)			4	Error
PSIP to CHI2	3	11% ⊕	10%	П	15%
PSIP to CHI1	24	11% ⊕	9%	П	14%
PSIP to CHIO	26	11% ⊕	10%	П	15%
CHI2 to JPSI	270	9% ⊕	8%	П	12%
CHI1 to JPSI	240	16% ⊕	6%	П	17%
CHIO to JPSI	88	17% ⊕	27%	П	32%
PSIP to ETAC	0.78	11% ⊕	21%	П	24%
JPSI to ETAC	1.13	€% ⊕	31%	П	31%

## Radiative widths: experimental overview

All current values are obtained combining  $e^+e^-$  and  $p_0$  data as follows:

$$\Gamma_{rad}(\Psi_i \to \gamma \Psi_f) = \Gamma_{tot}(\Psi_i) * BR(\Psi_i \to \gamma \Psi_f)$$

The fractional error is given by:

$$: \frac{\delta I_{tot}}{\Gamma_{tot}} \oplus \frac{\delta BR}{BR} = \frac{\delta I_{rad}}{\Gamma_{rad}}$$

The refitted values (*C.Patrignani*, *hep-ex/0104003*) are summarized below:

Transition	Rad.Width (keV)					Error
<b>PSIP</b> to CHI2	19	11%	⊕	12%	II	16%
PSIP to CHI1	23	11%	⊕	10%	П	15%
<b>PSIP</b> to CHI0	20	11%	⊕	17%	П	20%
CHI2 to JPSI	374	9%	⊕	6%	II	11%
CHI1 to JPSI	281	16%	⊕	5%	П	17%
CHI0 to JPSI	119	10%	$\oplus$	15%	П	18%
<b>PSIP</b> to ETAC	0.78	11%	$\oplus$	21%	II	24%
JPSI to ETAC	1.13	<b>6%</b>	$\oplus$	31%	II	31%

## Radiative widths: theory overview

- The PDG2000 values are compared with theory predictions:
- ref.A: Fayyazuddin and Mobarek, Phys.Rev.D48, 1220(1983) Д
- ref.B:Gupta et al., Phys.Rev.D39, 974 (1989)
- ref.C:Resag and Munz, Nucl.Phys. A590,735 (1995) Д
- ref.D:McClary and Byers, Phys.Rev. D28,1692 (1985) A

Transition	Rad. Width (kEr	ror	ref.A	ref.B	ref.C	ref.C	2 ref.D	ref	D2
PSIP to CHI2	22	15%	14		25	60	35	27	22
PSIP to CHI1	24	14%	20		63	36	48	31	23
PSIP to CHI0	26	15%	21		00	31	32	19	16
CHI2 to JPSI	270	12%	347	33	26 2	02	347	347	305
CHI1 to JPSI	240	17%	273	25	50 2	50	230	270	240
CHI0 to JPSI	103	32%	141	-	1	40	119	128	117

	Radiative v	vidths:	theory	/ over	view			
• The	e refitted values ( <i>c.Patr</i>	gnani,hep-ex/	0104003 <b>) a</b>	re compa	ared with	these th	leory	
A	ref.A: Fayyazuddin	and Moba	ek, Phys	s.Rev.D4	8, 1220(	1983)		
A	ref.B:Gupta et al., F	hys.Rev.D	39, 974	(1989)				
A	ref.C:Resag and M	unz, Nucl.F	hys. A59	90,735 (1	<b>995</b> )			
A	ref.D:McClary and I	3yers, Phy	s.Rev. D	28,1692	(1985)			
• The	errors on P->S width	s include	the syst (	errors on	BR(S->	(P)		
Transition	Rad.Width (keV) E	rror ref.A	A ref.B	ref.C	ref.C	2 ref.D	ref.D	2
PSIP to CHI	2	16%	14	25	09	35	27	22
<b>PSIP to CHI</b>	1 23	15%	20	29	36	48	31	23
PSIP to CHI	0 20	20%	21	20	31	32	19	16
CHI2 to JPS	374	17%	347	326	270	347 :	347	305
CHI1 to JPS	1 281	19%	273	250	250	230	270	240
CHIO to JPS	119	23%	141	117	140	119	128	117

#### $\psi' \Rightarrow \gamma \chi$ Branching Ratios

- All the BR's come from the inclusive photon spectrum in ψ' decays (Crystal Ball) Gaiser et al. Ph. Rev. D34,711 (1986)
- Crystal Ball was limited by charged tracker inefficiency: some photons are actually misidentified hadrons (punchthroughs).
- BES vs E760/E835 discrepancies suggest systematic shifts C.Patrignani, hep-ex/0104003

	<b>0.9</b> %	0.8%	0.8%
PDG2000	<b>9.3</b>	<b>8.7</b> ±	<b>7.8</b> ±
	%	%	%
NEWHT	7.1±1.2	$\textbf{8.4}\pm\textbf{0.8}$	<b>6.8±0.8</b>
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#### **M1 Branching Ratios**

- All the measurements have very low statistics.
- There are no further evidences of the  $\eta_{\rm c}'$  state at 3595 (see Pastrone's talk)
- The large stat error on BR( $J/\psi -> \gamma \eta_{\chi}$ ) affects all BR( $\eta_c -> X$ ): both stat and syst error would strongly benefit from a new measure.



FIG. 8. Simultaneous fits to the  $\eta_c$  mass in the  $\psi'$  and  $J/\psi$  inclusive photon spectra. The data are plotted in 2% bins in the photon energy. The preferred resolution value of  $\sigma_0 = 2.7\%$  is used in the fit. The spectra labeled (b) and (c) correspond to the photon selection criteria of the  $\chi$  analysis. The spectra labeled (c) employ a modified cut on the lateral photon energy pattern as described in the text.

### Scanning experiments

- Log Likelihood:  $\log L = \sum_i (n_i \ln \lambda_i \lambda_i \ln n_i!)$
- N.observed events, from convolution of beam profile and Breit-Wigner

$$\Lambda_{i} = \epsilon \,\alpha(Ldt)_{i} \int \left[ \sigma_{o,R} BW(e - M_{R} \Gamma_{R}) + \sigma_{bkg}(e) \right] g(e - E_{i} \sigma_{beam,i}) de$$

The beam profile is often well described by a gaussian:

$$g(e-E_{i},\sigma_{beam,i}) = \frac{1}{\sqrt{2\pi\sigma_{beam,i}}} \exp\left(\frac{(e-E_{i})^{2}}{2\sigma_{beam,i}^{2}}\right)$$

The Breit–Wigner for formation of resonance R (spin J) from e⁺e⁻ , p<sub>☉</sub> annihilation, and decay to a given channel  $\Psi_{\mathsf{out}}$  :

$$BW(e-M_{R,}\Gamma_{R}) = (2J+1)\frac{0.389GeV^{2}mb}{P_{cm}^{2}}\pi \left(1 + \frac{4(e-M_{R})^{2}}{\Gamma_{R}^{2}}\right)^{-1}BR_{i} + BR_{out}$$

#### J/小 Width (E760)

measuring the excitation curve on 2 orbits during the The accuracy of the J/v Width was obtained by an improved scanning technique (double scan): by same run, syst errors were kept down to 6 keV The same technique was used at the v': syst=16 keV



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excitation curves calculated using the best fit parameters.

squares.





FIG. 3. Events per unit luminosity for the energy scan at (a) the  $\chi_{c1}$ , (b) the  $\chi_{c2}$ , and (c) the  $\psi'$ . The solid line represents the best fit with the data. The dashed line shows a typical resolution in the center-of-mass energy (arbitrary vertical units).

### E835/00: scan of the $\chi_{\rm c0}$



→ 33 pb<sup>-1</sup> yielded the first measurement at 10% level of the  $\chi_{co}$  width, with ~550 events

- Syst.errors under study
- → Using the PDG value for BR,  $\Gamma(\chi_{c_0} \Rightarrow \gamma \psi)=66$ keV
- This stimulated a quest for new ψ' data.

## Contributes to $\Gamma_{rad}$ 's from FNAL

$\delta\pi/\pi$								2 7%	8%				3 7%	9 18%
ρ								0.8	0.7				0.7	0.7
<b>Fi*Bo/eV</b> Fractional error	Stat Syst			<b>1.67</b> $5\% \oplus 7\%$	$1.29  9\% \oplus 10\%$			3%	3%				3%	$1.7  9\% \oplus  1\%$
<b>Fractional error</b>	Stat. Syst		5 12% ⊕ 5%	9%⊕4%	$13\% \oplus 9\%$	<b>12% ⊕ 6%</b>		4%	5%				5%	0 10% ⊕ <mark>1%</mark>
<b>Ttot/MeV</b>			0.306	1.98	0.88	0.099				16.6				9.6
Nevents			1624	585	513	~4000		~7000	~3500	69		~500	~3100	544
Ldt /nb <sup>-1</sup>			1493	1160	1030	360		12392	7256	2573		1053	5982	32859
Resonance			PSIP	CH12	CHI1	ISdf		CH12	CHI1	CHI0		CH12	CHI1	CHI0
Experiment		E760					E835/96				E835/00			

### $p_{\bigcirc} \Rightarrow \psi' \Rightarrow \gamma\gamma\psi$ with E835

- Total number of ψ' formed in E835/96+E835/00:1M.
- ~2080  $\psi' \Rightarrow \gamma \psi \Rightarrow \gamma \psi e^+e^$ events reconstructed:

~480	~850	~40
CHI2	CHI1	CHIO

- Worse CCAL resolution w/ respect to C.Ball⇒  $\chi_1, \chi_2$  merge
- → BR( $\chi_{cJ}$  ⇒  $\gamma \psi$ )
- Angular distributions



## Access to higher multipoles

- When  $J_{i} \otimes J_{i} \neq 0$ , higher multipoles can be measured, through the interference terms in angular distributions:
- ▶ e.g.:  $d\Gamma(\Omega)/d\Omega = |E1|^{P} f_{E_{1}}(\Omega) + E1^{*M2} f_{1_{2}}(\Omega) + E1^{*E3} f_{1_{3}}(\Omega) + \dots$
- Measurements exist for the processes:
- > From pp :  $X_{cI,2} \rightarrow y J/\psi$
- R704: C.Baglin et al., Phys.Lett. B195,85 (1987)
- E760: T.Armstrong et al., Phys.Rev. D48,3037 (1993)
- E835: M.Ambrogiani et. al., in preparation
- > From  $e^+e^-$ :  $\psi' \to \gamma \chi_{cl,2} \to \gamma \gamma J/\psi$
- Crystal Ball: M.Oreglia et al., Phys.Rev.D25,2259(1982).

Crystal Ball-	> Acceptance for e, $\gamma(\theta_{cm} = \theta_{lab})$ : $ \cos(\vartheta)  < 0.94$	> Double reaction: $\psi' \rightarrow \chi_c \rightarrow \gamma \chi/\psi$	$\blacktriangleright \chi_{c_1}, \chi_{c_2}$ disentangling based on kin.fit (depend on calo resolution)	E760/E835:	> Acceptance for e, $\gamma(\theta_{cm} \# \theta_{lab})$ : $-0.60 < \cos(\theta_{cm,e}) < 0.65$	Single reaction (but 2 helicity states in input)	$\blacktriangleright$ $\chi_{c_1},\chi_{c_2}$ are directly formed	Roberto Mussa, Genoa Workshop on Charmonium, June 8,200
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$$W(\Omega) = \sum_{\lambda_{n-1}}^{1} B_{[\lambda]}^{2} \sum_{\nu,\nu'=-J}^{J} d_{\lambda\nu}^{J}(\vartheta) d_{\lambda\nu'}^{J}(\vartheta) A_{\nu} A_{\nu'} \sum_{\mu=\pm 1} \rho_{\mu-\nu',\mu-\nu'}(\vartheta',\phi')$$

 $\blacktriangleright$   $\rho_{\rm kck}$  is the J/ $\psi$ -> $e^+e^-$  density matrix

$$\Rightarrow B_{|\lambda|} = \langle \chi_c | T(J_z = \lambda) | p_{|0} \rangle, \ \Sigma B_{|\lambda|}^2 = 1. B_0(\chi_{c_1}) = 0.$$

$$A_v = <\chi_c |T(J_z = v)|\gamma J \Lambda v > , \Sigma A_v^2 = \Sigma a_k^2 =$$

➤ A<sub>v</sub> (helicity) vs a<sub>k</sub>(multipole) :





### ----> y J/y Angular Distributions :E835 fit $\chi_{c1,2}$

- Event samples: 2090  $\chi_{c1}$ , 5098  $\chi_{c2}$  events from 5C kin.fit
- Fitted parameters:
- Magnetic Quadrupole fractional amplitude:

$$a_{M2}(X_{cI,2}) \equiv a_2(X_{cI,2}) = \frac{M2}{\sqrt{EI^2 + M2^2 + E3^2}}$$

Electric Octupole fractional amplitude ( $\chi_{2,3}$  only): Д

$$a_{E3}(\chi_{c_2}) \equiv a_3(\chi_{c_2}) = \frac{E3}{\sqrt{EI^2 + M2^2 + E3^2}}$$

Helicity Zero squared fractional Amplitude ( $\chi_{co}$  only): A

$$B_0^2(X_{c_2} \to \overline{p} \ p)$$

- Unbinned Likelihood method on 3D angle space
- $\chi^2$  (Ndof~96) to check fitting method.

E835 results on angular distributions



## Angular distributions: Crystal Ball

- Events selected with 3C(μ<sup>+</sup>μ) or 5C(e<sup>+</sup>e<sup>-</sup>) kinematic fit
- Data samples: 921  $\chi_{c_1}$  and 441  $\chi_{c_2}$  events (from 0.8M  $\psi'$ )
- Unbinned likelihood fit on a5D angle space
- a'<sub>2</sub> (ψ'-> γχ) ,a<sub>2</sub> ( χ->ψ)
  fitted simultaneously



FIG. 15. Vectors and frames describing the cascade reaction  $\psi \rightarrow \gamma' \chi, \chi \rightarrow \gamma J/\psi, J/\psi \rightarrow l^+ l^-$ . In the laboratory frame  $e^{\pm}$  refer to the beam electrons; in the  $J/\psi$  frame  $l^{\pm}$  refer to the outgoing leptons.



Crystal Ball results on a<sub>2</sub>, a<sub>2</sub>

### **M2 results overview**

- $a_2(\chi_{c_1})$  : consistent results,  $\delta a_2(\chi_{c_1}) = 0.02$ 
  - $a_2(\chi_{c2})$  : large CB error justifies everything....  $\delta a_2(\chi_{c2})=0.03$
- $a_2(\chi_{c_1})/a_2(\chi_{c_2})$ : 2 $\sigma$  from theory predictions



## Theory expectations on a<sub>2</sub>

- Most theory papers neglect M2
- A calculation (with few misprints) can be found in
- Sebastian, Grotch, Ridener, Phys. Rev. D45, 3163(1992) Д

$$a_{2}(\chi_{cl}) = -(1+\kappa_{c})\frac{E_{\gamma}}{4m_{c}} \implies \Rightarrow -0.065 \, if \, \kappa_{c} = 0$$
$$a_{2}(\chi_{c2}) = -(1+\kappa_{c})\frac{3}{\sqrt{5}}\frac{E_{\gamma}}{4m_{c}} \implies \Rightarrow -0.096 \, if \, \kappa_{c} = 0$$

 $\kappa_{c}^{}$  is the anomalous magnetic moment of the charm quark

The ratio  $a_2(\chi_{c_1})/a_2(\chi_{c_1})$  should then be 0.68, canceling out any κ<sub>c</sub> or m<sub>c</sub> dependence

# Perspectives in future e<sup>+</sup>e<sup>-</sup> Experiments

A high statistics (~fb<sup>-1</sup>)sample at <sup>\fy</sup> will allow a precise measurement of the ratio:

$$\overline{\Xi} = \frac{BR(X_c \to \gamma J/\psi)}{BR(X_c \to p \overline{p})} \propto \frac{N(\psi' \to \gamma X_c \to \gamma J/\psi)}{N(\psi' \to \gamma X_c \to p \overline{p})}$$

with little systematic dependence on other processes.

The radiative width will be extracted from:

$$\Gamma(\chi_{c} \to \gamma J/\psi) = \sqrt{\left[\Gamma(\chi_{c} \to \gamma J/\psi) * \Gamma(\chi_{c} \to \overline{p} p)\right]_{E835}} * \overline{\mathcal{Z}}_{CLEO-}$$

C

The stat error is then given by:

$$\frac{\delta \Gamma_{rad}}{\Gamma_{rad}} = \frac{1}{2} \left\{ \frac{\delta \Pi}{\Pi} \oplus \frac{\delta \Xi}{\Xi} \right\}$$

where  $\Pi = [\Gamma(\chi_c \to \gamma J/\psi) * \Gamma(\chi_c \to \overline{p} p)]_{E835}$ 

#### **Yields at CLEO-c**

Tot <sup>w</sup> produced	1.00E+08	Frac error
$\psi' - \gamma \chi_2$	7.80E+06	0.04%
> γψ>γe⁺e⁻	6.24E+04	0.40%
©d <	7.80E+02	3.58%
$\psi' \longrightarrow \gamma \chi_{\tau}$	8.70E+06	0.03%
> γψ>γe⁺e⁻	1.41E+05	0.27%
©]d <	8.70E+02	3.39%
$\psi' \longrightarrow \gamma \chi_o$	9.70E+06	0.03%
> γψ>γe⁺e⁻	3.80E+03	1.62%
©]d <	3.88E+03	1.61%
$\psi' \rightarrow m_c$	2.80E+05	0.19%
₫ <b>d</b> <	3.36E+02	5.46%
$\mathcal{M} <$	8.40E+01	10.91%

### Summary, conclusions

- $\Gamma_{rad} = \Gamma_{tot}^{*}BR_{rad} -> complementarity$
- BR's from Crystal Ball : 16y old
- $\Gamma_{tot}$  's from E760 except  $\chi_{c0}$
- E835: stats down to 5% level, but....
- M2 terms = ~10%E1 at  $\chi_{c2}$ , 0 at  $\chi_{c1}$
- It's e<sup>+</sup>e<sup>-</sup> time again:CLEO-c