

4 New Meson States ...

3 New Puzzles

Steve Godfrey
Carleton University
godfrey@physics.carleton.ca

- Deconstructing the D_{sj} states
- Charmonium options for the $X(3872)$
- Options for the SELEX state $D_{sJ}(2632)$
- Summary



1. Deconstructing the D_{sj} states



April 11, 2003 *BaBar reports observation of a narrow meson near $2.32 \text{ GeV}/c^2$*
The BaBar Collaboration has observed a narrow state near $2.32 \text{ GeV}/c^2$ in the inclusive $D_s^+ \pi^0$ invariant mass distribution from 91 fb^{-1} of e^+e^- annihilation data...

the tentative spin-parity assignment is confirmed, then the low mass, small width, and decay mode of the $D_{sJ}^*(2317)^+$ are quite different from those predicted by quark potential models. Since a charm-strange meson of this mass contradicts the current models of charm meson spectroscopy, either these models need modification or the state is of a different type altogether, such as a four-quark state.

—Ray F. Cowan *BaBar* Docmaster

What's behind all the excitement?

- Expect the $j=1/2$ states to be above DK and D^*K threshold
- Expect broad S-wave decays

But states are below threshold and very narrow!



Charmed mesons:

- Almost all the effort has concentrated on the D_{sJ} states
- *But the D states also contain important information and could hold the key*
- Can the experimental measurements be accommodated by theory?

D_2^* (PDG)	$M=2459 \pm 2$ $\Gamma=23 \pm 5$	Belle	CLEO
D_1 (avg)	$M=2438 \pm 30$ $\Gamma=329 \pm 84$	$M=2427 \pm 36$ $\Gamma=384^{+130}_{-105}$	$M=2461 \pm 53$ $\Gamma=290 \pm 43$
D_1 (PDG)	$M=2422.2 \pm 1.8$ $\Gamma=18.9^{+4.6}_{-3.5}$	Belle	Focus
D_0^* (avg)	$M=2351 \pm 27$ $\Gamma=262 \pm 51$	$M=2308 \pm 30$ $\Gamma=276 \pm 66$	$M=2407 \pm 41$ $\Gamma=240 \pm 81$



Masses:

Good agreement with predicted splittings.

Strong Decays:

Decay		Theory	Expt
$D_2^* \rightarrow D^* \pi + D\pi$	$\frac{3}{10} D^2 q^5 + \frac{1}{5} D^2 q'^5$	63	23
$D_1 \rightarrow D^* \pi$	$\frac{1}{2} [\sin^2(\theta + \theta_0) S^2 q + \cos(\theta + \theta_0) D^2 q^5]$	26	18.9
$D_1 \rightarrow D^* \pi$	$\frac{1}{2} [\cos^2(\theta + \theta_0) S^2 q + \sin(\theta + \theta_0) D^2 q^5]$	250	329
$D_0^* \rightarrow D\pi$	$\frac{1}{2} S^2 q$	290	262

$\theta_0 = 35.3^\circ$ (arises from Clebschs)

In HQL one D_1 becomes pure S-wave the other pure D-wave

Good agreement between theory and experiment



Radiative Transitions

- Transitions probe the internal structure
- Radiative E1 transitions given by:

$$\Gamma(i \rightarrow f + \gamma) = \frac{4}{27} \alpha \langle e_Q \rangle^2 \omega^3 (2J_f + 1) \left| \langle {}^{2s+1}S_{J'} | r | {}^{2s+1}P_J \rangle \right| S_{if}$$

$$\langle e_Q \rangle = \frac{m_q e_c + m_c e_{\bar{q}}}{m_c + m_q}$$

$$D_{s1}^{3/2} = {}^1P_1 \cos \theta + {}^3P_1 \sin \theta$$

$$D_{s1}^{1/2} = -{}^1P_1 \sin \theta + {}^3P_1 \cos \theta$$

$\theta_{uc} = -26^\circ$

Initial state	Final State	Width	BR
D ^{*+} ₂ (2502)	D ^{*+} γ	590 keV	2.5%
D ₁ (2456)	D [*] γ	87 keV	0.44%
	Dγ	635 keV	3.2%
D [*] ₁ (2467)	D [*] γ	381 keV	~10 ⁻³
	Dγ	163 keV	~10 ⁻³
D ^{*+} ₀ (2308)	D ^{*+} γ	288 keV	10 ⁻³

• Should be observable

• Can be used to determine mixing angle!

$$\frac{\Gamma({}^3P_1 \rightarrow {}^3S_1 + \gamma)}{\Gamma({}^1P_1 \rightarrow {}^1S_0 + \gamma)} = \frac{\omega_t^3 |\langle r \rangle_t|^2 \cos^2 \theta}{\omega_s^3 |\langle r \rangle_s|^2 \sin^2 \theta}$$

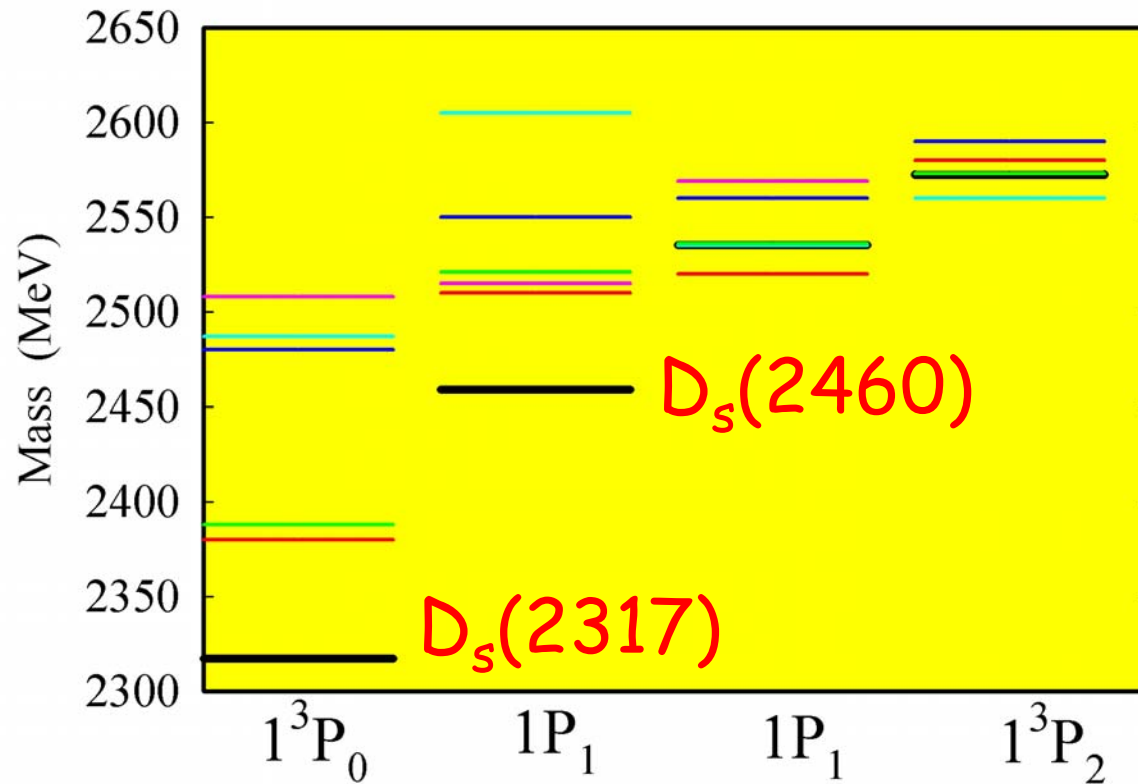


Good agreement between quark model
Predictions and experiment for charmed
P-wave mesons

Models explaining the $D_s(2317)$ must also
describe the D L=1 states



Charm-Strange mesons:



Strong Decays

In heavy quark limit 4 L=1 states grouped into 2 doublets
 Characterized by angular momentum of light quark: $j=3/2, 1/2$
 $j=3/2$ are predicted to be relatively narrow
 identified with $D_{s1}(2536)$ and $D_{sJ}(2573)$

		Theory	Expt
$D_{s2}^* \rightarrow D^* K$ + DK	$\frac{2}{5} D^2 q^5 + \frac{4}{15} D^2 q'^5$	21	15^{+5}_{-4}
$D_{s1} \rightarrow D^* K$	$\frac{2}{3} [\sin^2(\theta + \theta_0) S^2 q + \cos(\theta + \theta_0) D^2 q^5]$	0.3	<2.3

Good agreement with model predictions

$j=1/2$ predicted to be broad and decay to DK and D^*K
 not previously observed

But $D_{sJ}^*(2317)$ below DK threshold
 $D_{sJ}(2460)$ below D^*K threshold

Only $D_s \rightarrow D_s^* \pi^0$ allowed but violates I-spin so small



Radiative Transitions: expected to have large BR's

Initial state)	Final State	Width	BR	$/D_s\pi^0$	$/D_s\pi^0$
$D_{s0}^{*+}(2317)$	$D_{s\gamma}^{*+}$	1.9 keV	16%	0.19	<0.059 (CLEO)
					<0.18 (Belle)
	$D_s^+\gamma$	0		0	<0.052 (CLEO)
					<0.05 (Belle)
	$D_s\pi^0$	~10 keV	84%		
$D_{s1}(2463)$	$D_{s\gamma}^*$	5.5 keV	24%	0.56	<0.16 (CLEO)
					<0.31 (Belle)
					0.274 ± 0.049 (Babar)
	$D_s\gamma$	6.2 keV	27%	0.63	0.44 ± 0.17 (Babar)
					0.55 ± 0.15 (Belle)
					<0.49 (CLEO)
	$D_s\pi^0$	~10 keV	43%		
	$D_s\pi\pi$	~1.6 keV	7%	0.16	0.14 ± 0.04 (Belle)



Can reconcile the discrepancy between

BR for $D_{s1}(2463) \rightarrow D_s \gamma$

And

limits for $D_{s0}^{*+}(2317) \rightarrow D_s^{*+} \gamma$

by taking $\theta = \pm 20$

Can be used to determine mixing angle

$$\frac{\Gamma(^3P_1 \rightarrow ^3S_1 + \gamma)}{\Gamma(^1P_1 \rightarrow ^1S_0 + \gamma)} = \frac{\omega_t^3 |\langle r \rangle_t|^2 \cos^2 \theta}{\omega_s^3 |\langle r \rangle_s|^2 \sin^2 \theta}$$

The problem is the mass predictions

Once the masses are fixed the narrow widths follow

My view is that the strong coupling to DK almost certainly plays an important role in the solution to this puzzle

(e.g. Van Beveren & Rupp Phys. Rev.Lett. 91, 012003 (2003))



2. Charmonium Options for the X(3872)

T.Barnes, S.Godfrey, Phys Rev D69, 050400 (2004) [hep-ph/0311162]

Eichten, Lane & Quigg, Phys Rev D69, 094019 (2004) [hep-ph/0401210]

Barnes, Godfrey & Swanson, in preparation

New state 1st observed by Belle: X(3871) hep-ex/0309032

Observation of a new narrow charmonium state in exclusive

$B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays

$M = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}$

$\Gamma < 2.3 \text{ MeV}$ at 90% C.L.

width consistent with detector resolution.

1. $D^0 D^{*0}$ molecule
2. A charmonium hybrid
3. 1^3D_2 state?

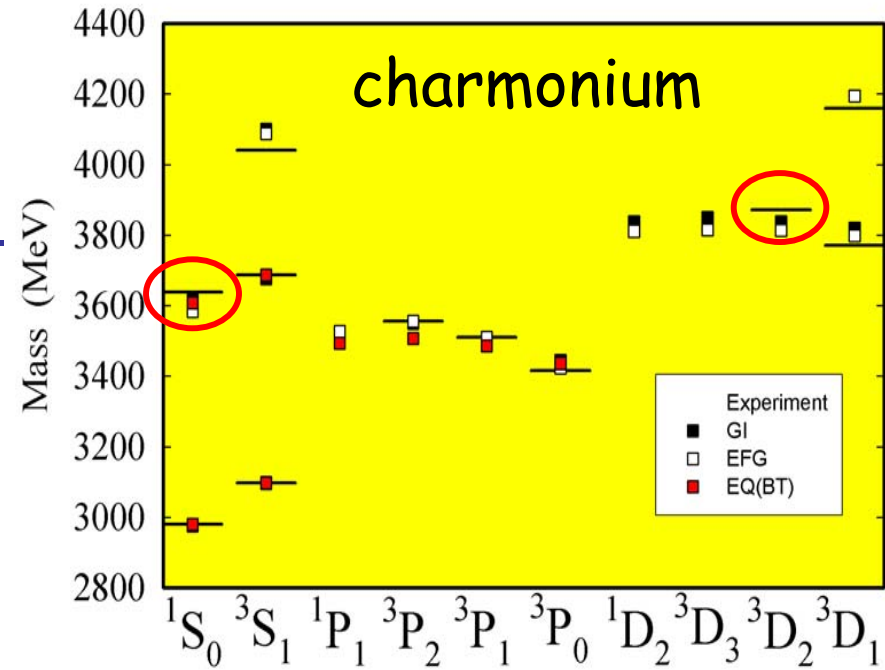


1³D₂ state?

Most models predict $\psi(1^3D_2)$ mass to be ~70 MeV lower than X(3872). BUT they reproduce the $Y(1^3D_2)$ mass.

No models appear to accommodate $\psi(3770)$ and X(3872) in the same 1³D_J triplet!

Can coupled channel effects and $\psi(1^3D_1)$ - $\psi(2^3S_1)$ mixing change this?



D-states are narrow as long as below the DD* threshold

- Predict:
$$\frac{BR(\psi(1^3D_2) \rightarrow \gamma\gamma J / \psi)}{BR(\psi(1^3D_2) \rightarrow \pi^+\pi^- J / \psi)} \sim 3$$

- But:
$$\frac{BR(X(3872) \rightarrow \gamma\chi_{c1})}{BR(X(3872) \rightarrow \pi^+\pi^- J / \psi)} < 0.89 \text{ (90\% CL)}$$
 Belle hep-ex/0309032



Charmonium Options for the X(3872)

- Consider all 1D and 2P cc possibilities
- Assume $M=3872$ MeV
 - calculate radiative widths and
 - strong decay widths

Strong Decays:

1. Zweig-allowed open-charm decays (DD)

- expect 1^3D_2 and 1^1D_2 to be narrow because can't decay to DD due to parity and below DD^* threshold
- but 1^3D_3 also narrow due to angular momentum barrier

2. Annihilation type decays

eg.
$$\Gamma(^3D_J \rightarrow ggg) = \frac{10\alpha_s^3}{9\pi} C_J \frac{|R_D''(0)|^2}{m_Q^6} \ln(4m_Q \langle r \rangle) \quad \text{etc.}$$

3. Hadronic transitions



TABLE IV: Partial widths and branching fractions for strong and electromagnetic transitions in scenario 1: We assume in all cases that the initial $c\bar{c}$ state has a mass of 3872 MeV. Details of the calculations are given in the text.

Initial state	Final state	Width (MeV)	B.F. (%)
1^3D_3	DD	4.04	84.2
	ggg	0.18	3.8
	$J/\psi\pi\pi$	0.21 ± 0.11	4.4
	$\chi_{c2}(1^3P_2)\gamma$	0.37	7.7
	Total	4.80	100
1^3D_2	ggg	0.08	10.8
	$J/\psi\pi\pi$	0.21 ± 0.11	28.4
	$\chi_{c2}(1^3P_2)\gamma$	0.09	12.2
	Total	0.74	100
1^3D_1	DD	184	98.9
	ggg	1.15	0.6
	$J/\psi\pi\pi$	0.21 ± 0.11	0.1
	$\chi_{c1}(1^3P_1)\gamma$	0.20	0.1
	Total	186	100
1^1D_2	gg	0.19	22.1
	$\eta_c\pi\pi$	0.21 ± 0.11	24.4
	$h_c(1^1P_1)\gamma$	0.46	53.5
	Total	0.86	100

2^3P_2	DD	21.1	82.4
	gg	4.4	17.2
	$\psi'(2^3S_1)\gamma$	0.06	0.2
	$J/\psi(1^3S_1)\gamma$	0.04	0.2
	Total	25.6	100
2^3P_1	$q\bar{q}g$	1.65	95.9
	$\psi'(2^3S_1)\gamma$	0.06	3.5
	$J/\psi(1^3S_1)\gamma$	0.01	0.6
	Total	1.72	100
2^3P_0	DD	13.7 (see text)	24.6
	gg	42.	75.3
	$\psi'(2^3S_1)\gamma$	0.07	0.1
	$\psi'(1^3D_1)\gamma$	0.02	4×10^{-2}
	Total	55.8	100
2^1P_1	ggg	1.29	81.6
	$gg\gamma$	0.13	8.2
	$\eta'_c(2^1S_0)\gamma$	0.09	5.7
	$\eta_c(1^1S_0)\gamma$	0.07	4.4
	Total	1.58	100

too wide

too wide

too wide



So far haven't distinguished between $C=+$ or $C=-$

• $J/\psi \pi\pi$ implies $C=-$ so expect $\pi^0\pi^0$ final state in ratio of 1/2

• $J/\psi \rho$ implies $C=+$ but only $\pi^+\pi^-$ final state

Therefore observation or non observation of $\pi^0\pi^0$ distinguishes C

ie. $C=-$ gives 1^3D_2 1^3D_3 or 2^1P_1

While $C=+$ gives 1^1D_2 or 2^3P_1

Radiative decays can then distinguish between the remaining possibilities

NOTE: $\frac{BR(X \rightarrow \gamma\chi_{c2})}{BR(X \rightarrow \pi^+\pi^- J/\psi)} < 1.1$ (90% CL) tests 1^3D_3
Belle

angular distribution analysis rules out 2^1P_1

Differences of $\pi^0\pi^0 / \pi^+\pi^-$ from 1/2 suggests DD^* admixtures

Probably the most useful result is that all 4 D-wave states should be observable in B-decay!

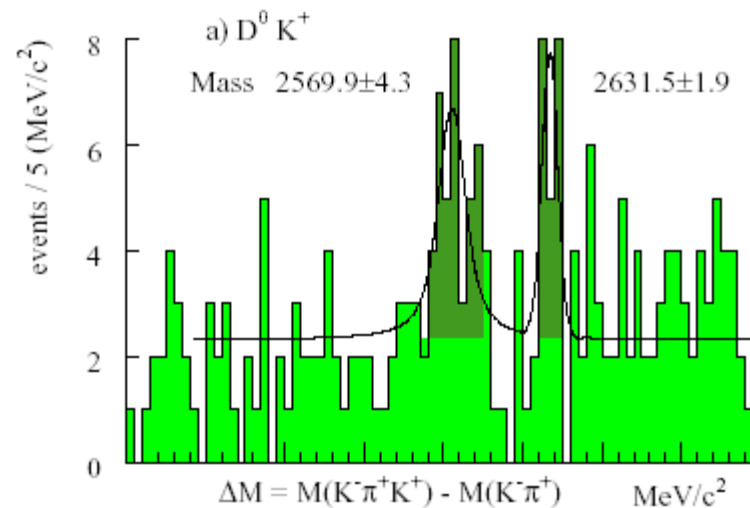
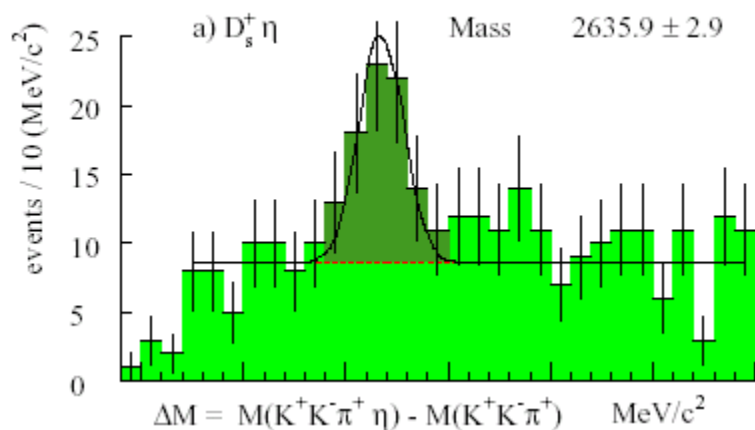


3. Options for the $D_{sJ}(2632)$

Barnes, Close, Dudek, Godfrey & Swanson [hep-ph/0407120]

First Observation of a Narrow Charm-Strange Meson $D_{sJ}^+(2632) \rightarrow D_s^+ \eta$ and $D^0 K^+$
(The SELEX Collaboration) hep-ex/0406045

See talk by J. Russ



Seen in hadro-production in $D_s^+ \eta$ and $D^0 K^+$
 $M = 2632.6 \pm 1.6 \text{ MeV}/c^2$ $\Gamma < 17 \text{ MeV}/c^2$ at 90% C.L.

$$\Gamma(D^0 K^+) / \Gamma(D_s^+ \eta) = 0.16 \pm 0.06$$

(Not seen by CLEO, Belle, Babar)



Possibilities:

- $2^3S_1(cs)$ State
- cs Hybrid
- 2-meson molecule

Most plausible cs state is 2^3S_1 with $M(2^3S_1)=2730$ MeV
& $M(1^3D_1)=2900$ MeV

masses could be shifted by mixing with 2-meson continuum

Note:

- Low observed mass shared with $K^*(1414)$ state
- Decays of $K^*(1414)$ also disagree with models
- Maybe $K^*(1414)$ & $D_{sJ}(2632)$ related



Assuming the $D_{sJ}(2632)$ is $n^{(2S+1)}L_J = 2^3 S_1(c\bar{s})$ with $M=2632$

The allowed open-flavour decay modes are: DK , $D_s\eta$, D^*K

SELEX finds:

$$BR(DK / D_s\eta) = 0.32 \pm 0.12 \quad (\text{assuming } BR(D^0K^+) = BR(D^+K^0))$$

In 3P_0 model for preferred value of β :

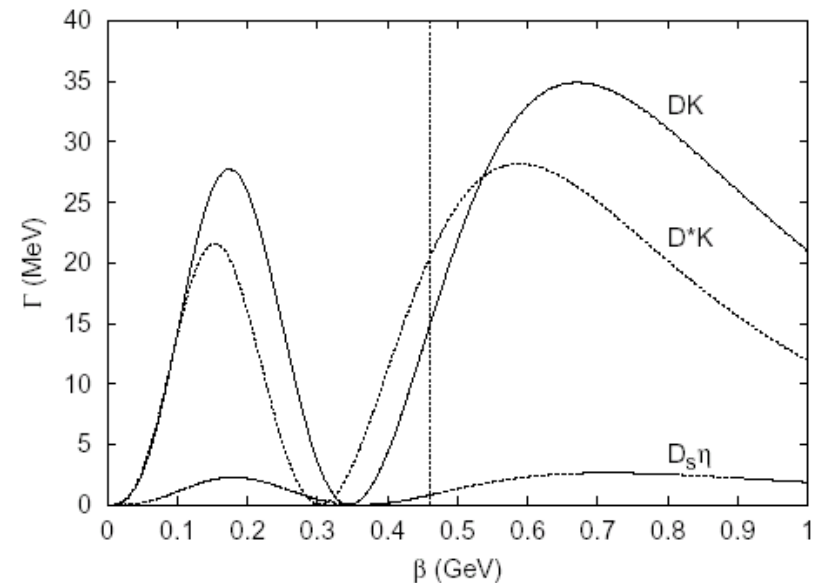
$$\Gamma(D^*K) > \Gamma(DK) \gg \Gamma(D_s\eta)$$

$$\Gamma(D_{sJ}(2632)) = 36 \text{ MeV}$$

$$\Gamma(DK) / \Gamma(D_s\eta) \approx 9$$

Not consistent with experiment

Search for D^*K mode and determination of BR's are useful tests



2^3S_1 - 1^3D_1 Mixing could alter the ratio of BR's

- Mixing could be generated by coupling to meson-mesons states
- Assume:

$$|D_{sJ}(2632)\rangle = \cos\theta |2^3S_1\rangle + \sin\theta |1^3D_1\rangle$$

- Suppression of DK to $D_s\eta$ widths implies:

$$\theta \approx 155^\circ \text{ or } -25^\circ$$

- Where both DK to $D_s\eta$ widths are very small.
This tuning seems unlikely to us.
- Further estimate:

$$\Gamma(2^3S_1(c\bar{s}) \rightarrow D_s^* + \pi\pi) \approx 220 \text{ keV} \Rightarrow BR \geq 1\%$$



Summary:

D_{sj} states

- The D $L=1$ states are described well by the quark model
- Need to confirm them
- Radiative transitions are a crucial test of the D_{sJ} states

$X(3872)$

- $\pi^0\pi^0$ VS $\pi^+\pi^-$ to determine C -conjugation
- Radiative decays can then distinguish between the remaining possibilities
- All 4 D -wave states should be observable in B -decay!

SELEX $D_{sj}(2632)$ state

- If 2^3S_1 state expect to see D^*K decay mode
- Should also see it in B decays

$$\Gamma(2^3S_1(c\bar{s}) \rightarrow D_s^* + \pi\pi) \approx 220 \text{ keV} \Rightarrow BR \geq 1\%$$

- The 1^3D_1 state should be ~ 200 MeV higher in mass



First Meeting of the
APS Topical Group on Hadronic Physics
24 - 26 October 2004 - Fermilab

GHP 2004

Topics Include

- Light / Heavy Quark Mesons
- Glueballs, Hybrids, and Multiquarks
- Baryons
- Lattice Gauge Theory
- Effective Lagrangians
- Quark Models
- RHIC
- Hadronic Structure
- Future Facilities

24 - 26 October 2004
Fermilab - Batavia, Illinois

Organizing Committee

Ted Barnes (Chair)	ORNL / UT Knoxville, TN
Steve Godfrey	Carleton University, Canada
Alexey Petrov	Wayne State University, MI
Cynthia Szama	FNAL
Eric Swanson	University of Pittsburgh, PA
Suzanne Weber	FNAL

Advisory / Program Committee

Frank Close	Oxford, UK
Alex Dzierba	Indiana University, IN
Estia Eichten	FNAL
Wally Melnitchouk	Jefferson Lab
Chris Quigg	FNAL
Anthony Thomas	Adelaide, Australia / Jefferson Lab
William Zajc	Columbia University, NY

Contact: Cynthia Szama, szama@fnal.gov
Website: <http://fafnir.phyast.pitt.edu/GHPM/>

