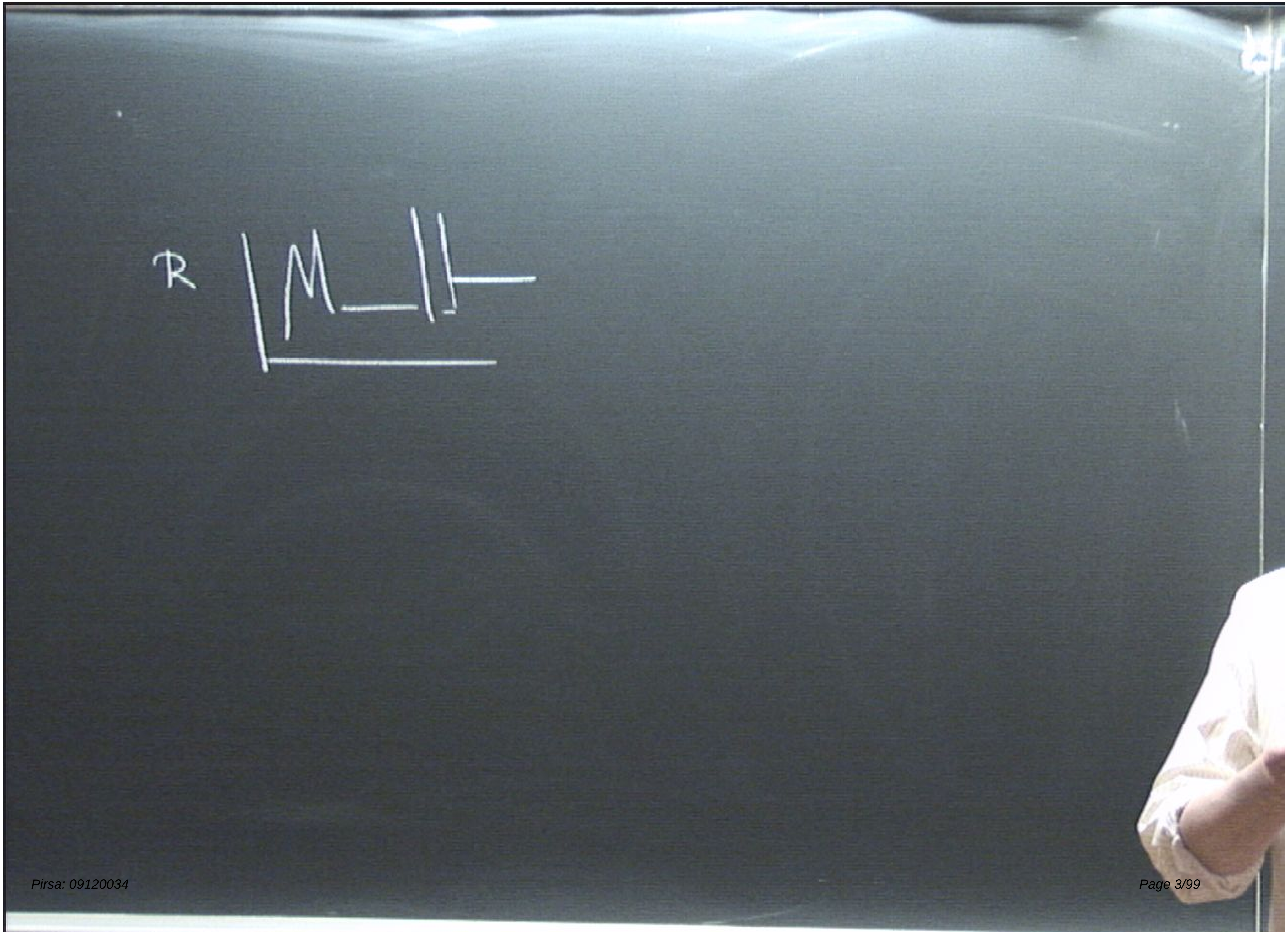
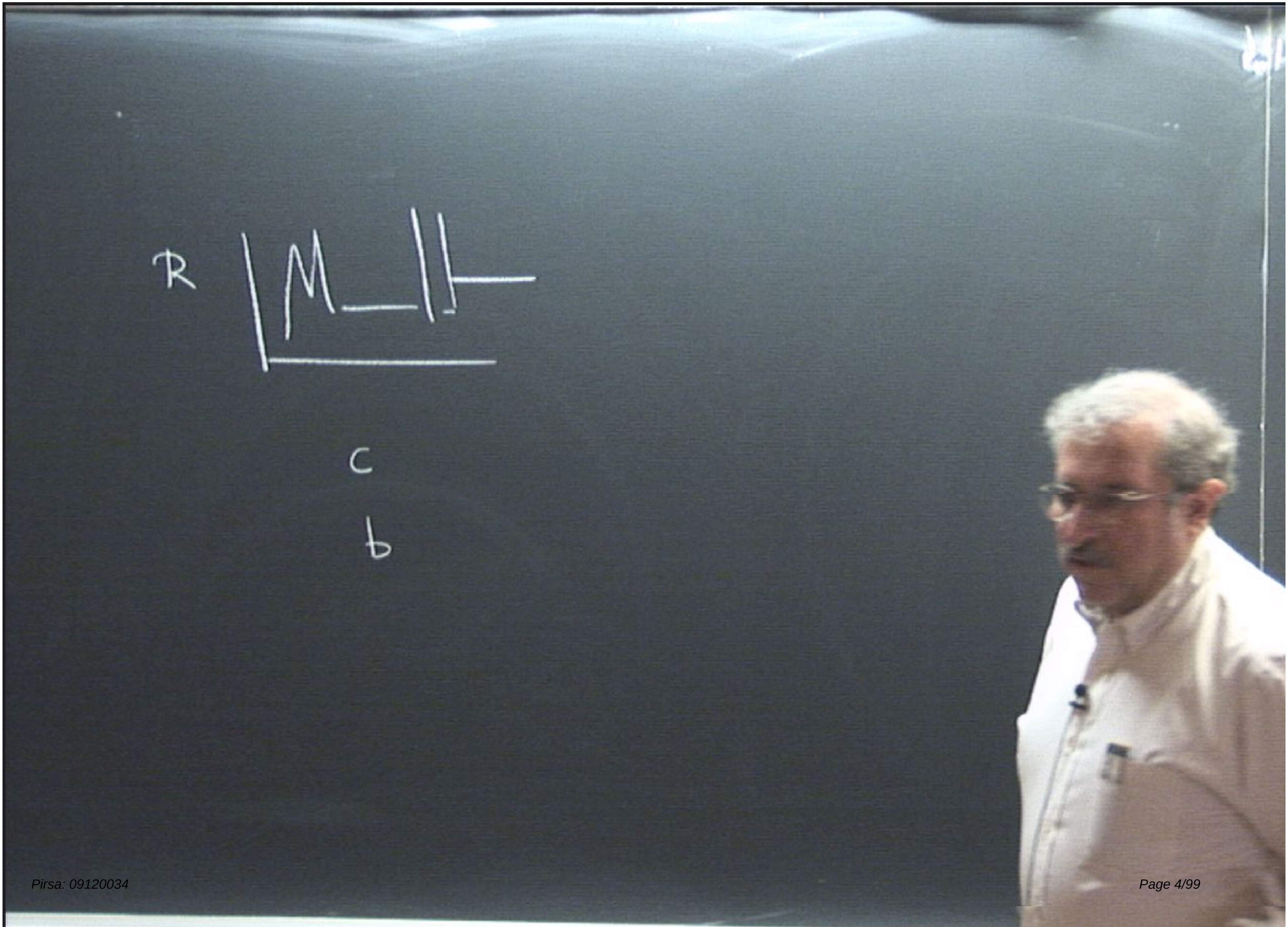
Title: Standard Model - Review (PHYS 622) - Lecture 4

Date: Dec 03, 2009 09:00 AM

URL: http://pirsa.org/09120034

Abstract:


R


R
c
b

$c\bar{c}$ charmonium

$b\bar{b}$ bottomonium

quarkonium

positronium e^+e^-

$c\bar{c}$ charmonium

$b\bar{b}$ bottomonium

quarkonium

positronium e^+e^-

R 

$\mathcal{H} =$

$R_y = \frac{1}{2}\frac{\alpha^2 mc^2}{n^2}$

$c\bar{c}$ charmonium

$b\bar{b}$ bottomonium

quarkonium

positronium $e^+ e^-$

$\mathcal{H} =$

$$R_y = \frac{1}{2} \frac{\alpha^2 m c^2}{n^2}$$

mc^2

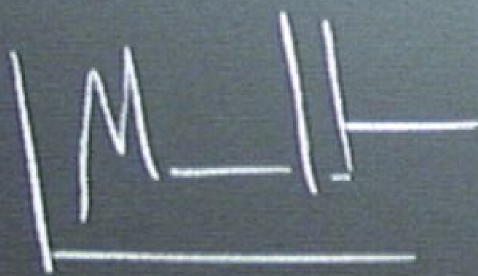
$c\,\bar{c}$ charmonium

$b\,\bar{b}$ bottomonium

$\alpha m c = 1/a_0$ quarkonium

$\alpha^2 m c^2$

R



positronium $e^+ e^-$

$H =$

$R_y = \frac{1}{2} \frac{\alpha^2 mc^2}{n^2}$

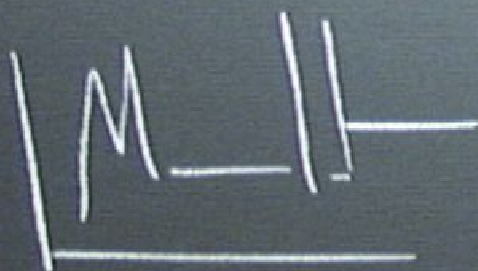
mc^2

$c \bar{c}$ charmonium

$b \bar{b}$ bottomonium

$\alpha mc = 1/a_0$ quarkonium

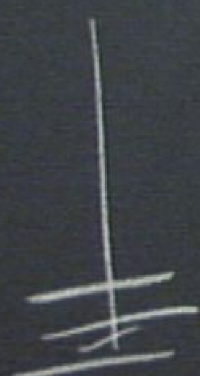
$\alpha^2 mc^2$

R 

positronium e^+e^-

$E_n = -R_y \frac{1}{n^2}$

$R_y = \frac{1}{2}\alpha^2 \mu c^2$



— mc^2

$\alpha mc = 1/a_0$

$\alpha^2 mc^2$

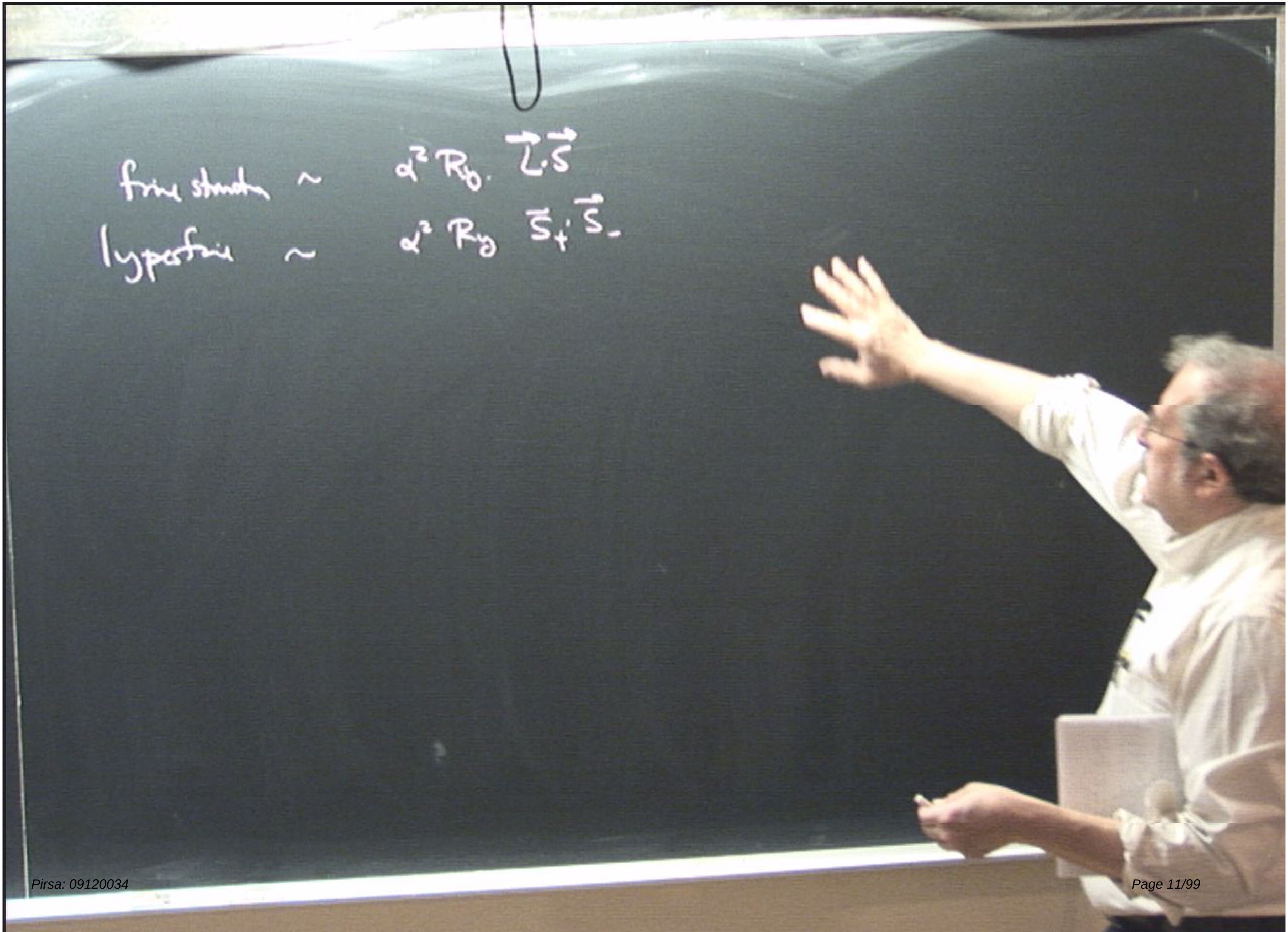
$c\bar{c}$ charmonium

$b\bar{b}$ bottomonium

quarkonium

positron

$\mu = \frac{1}{2} m_e$


fine structure ~ $\alpha^2 Ry.\ \vec{L}\cdot\vec{S}$
hyperfine ~ $\alpha^2 Ry\ \vec{S}_+\cdot\vec{S}_-$

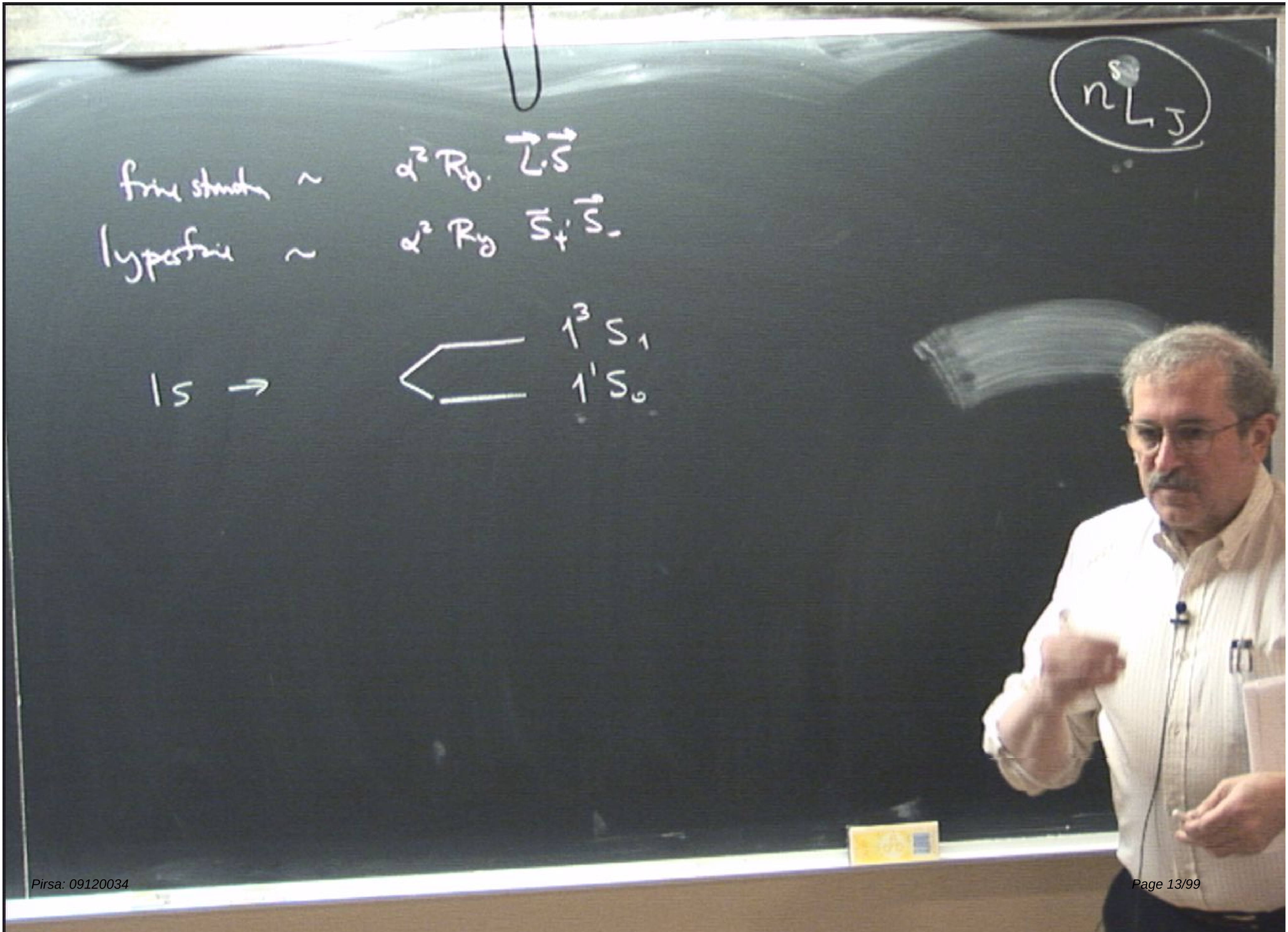
fine structure $\sim \quad \alpha^2 R_y \, \vec{L}\cdot\vec{S}$

hyperfine $\sim \quad \alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$

$1s \rightarrow \quad < \quad 1^1S_0$

$n^S L_J$

n

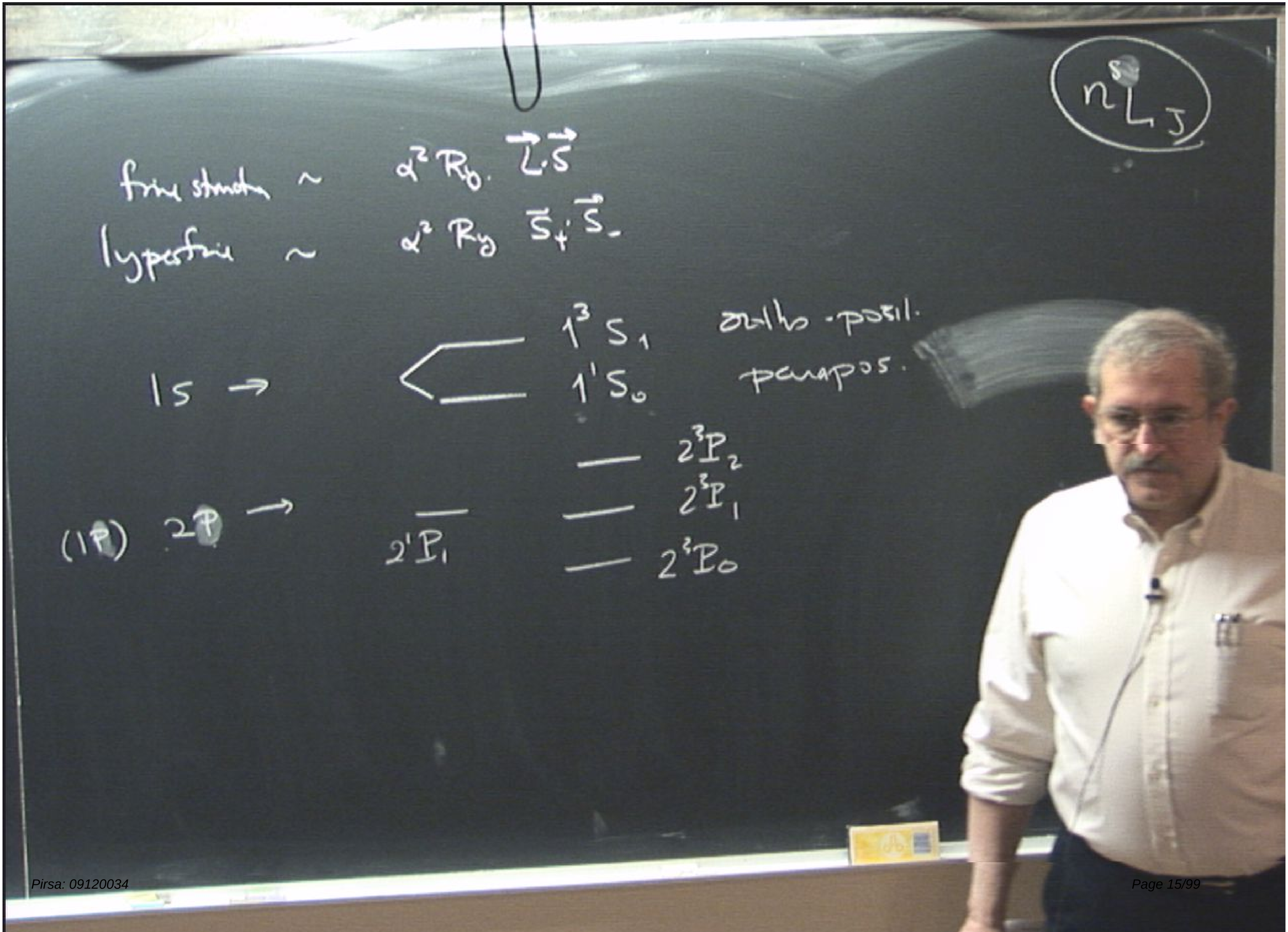

fine structure ~ $\alpha^2 R_y \, \vec{L}\cdot\vec{S}$
hyperfine ~ $\alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$
$1s \rightarrow$
1^3S_1
1^1S_0
$n^{2S+1}L_J$

$n^{S}L_{J}$

fine structure ~ $\alpha^2 R_y \, \vec{L}\cdot\vec{S}$

hyperfine ~ $\alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$

$1s \rightarrow$
- 1^3S_1 ortho-posit.
- 1^1S_0 parapos.



$n^{S}L_J$
fine structure ~ $\alpha^2 R_y \, \vec{L}\cdot\vec{S}$
hyperfine ~ $\alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$
$1s \rightarrow$
1^3S_1 ortho-posit.
1^1S_0 para-pos.
2^3P_2
2^3P_1
(1P) 2P $\rightarrow$
2^1P_1
2^3P_0

$n^{S}L_J$

fine structure ~ $\alpha^2 R_y \, \vec{L}\cdot\vec{S}$

hyperfine ~ $\alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$

$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$

$P = (-1)$

1s → 1^3S_1 ortho-posit.

1^1S_0 para-pos.

(1P) 2P → 2^1P_1

2^3P_2

2^3P_1

2^3P_0

fine structure $\sim \alpha^2 R_y\, \vec{L}\cdot\vec{S}$

hyperfine $\sim \alpha^2 R_y\, \vec{S}_+\cdot\vec{S}_-$

$n^{S}L_J$

$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$

$P = (-1)(-1)^{L}$

$P = -1$

$1s \rightarrow$ 1^3S_1 ortho-posit.

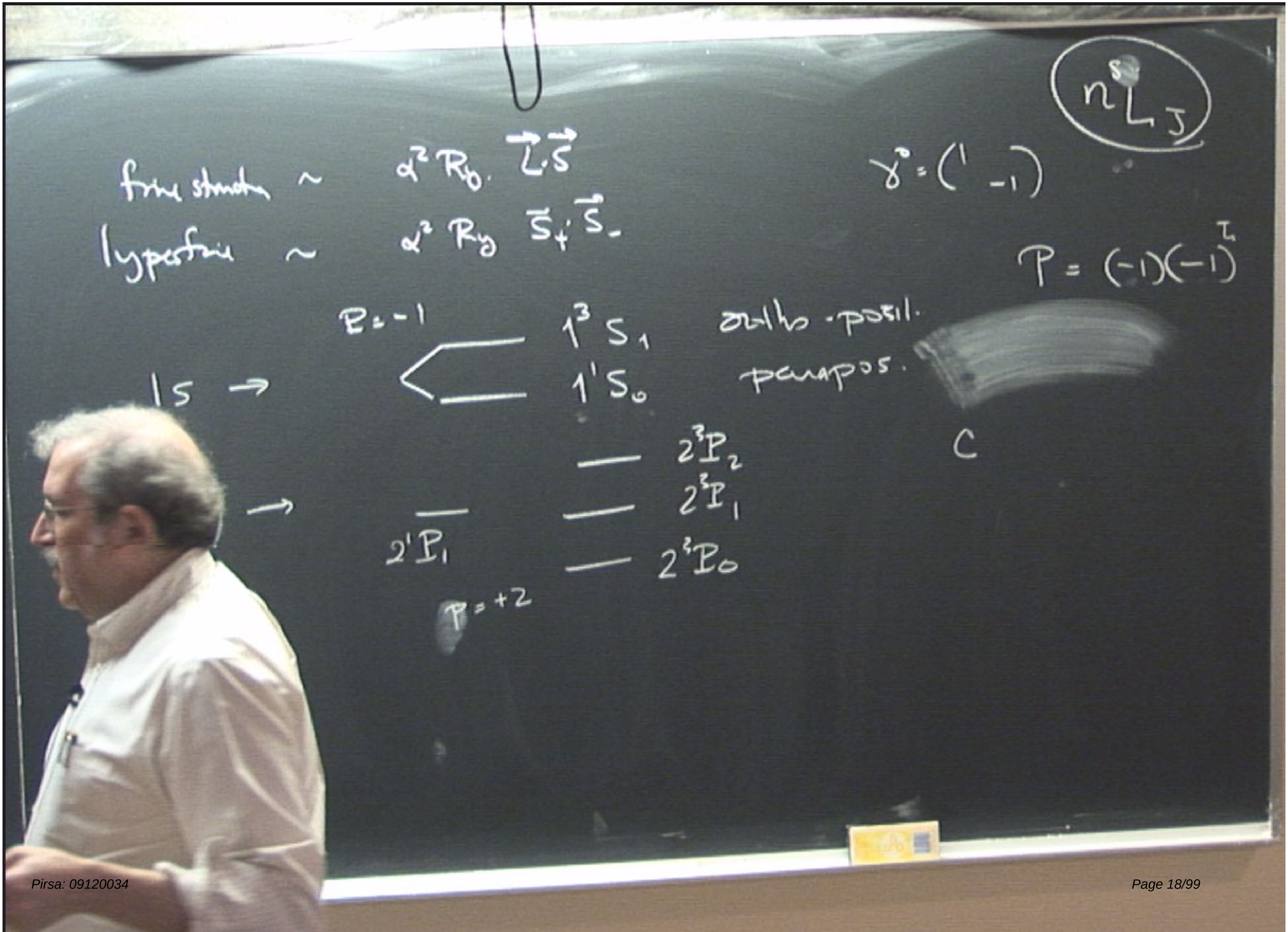
1^1S_0 parapos.

2^3P_2

$(1P)\ 2P \longrightarrow$ 2^3P_1

2^1P_1 2^3P_0

$P = +2$


$n^{2S+1}L_J$
fine structure ~ $\alpha^2 R_y\, \vec{L}\cdot\vec{S}$
hyperfine ~ $\alpha^2 R_y\, \vec{S}_+\cdot\vec{S}_-$
$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$
$P = (-1)(-1)^L$
$P = -1$
1^3S_1 ortho-posit.
1s →
1^1S_0 parapos.
C
2^3P_2
→
2^3P_1
2^1P_1
2^3P_0
$P = +2$

fine structure $\sim \alpha^2 R_y\, \vec{L}\cdot\vec{S}$

hyperfine $\sim \alpha^2 R_y\, \vec{S}_+\cdot\vec{S}_-$

$n^{S}L_J$

$\gamma^0 = \begin{pmatrix}1 & \\ & -1\end{pmatrix}$

$P = (-1)(-1)^{L}$

$P = -1$

$1s \to$ 1^3S_1 ortho-posit.

1^1S_0 para-pos.

$C = (-1)(-1)$

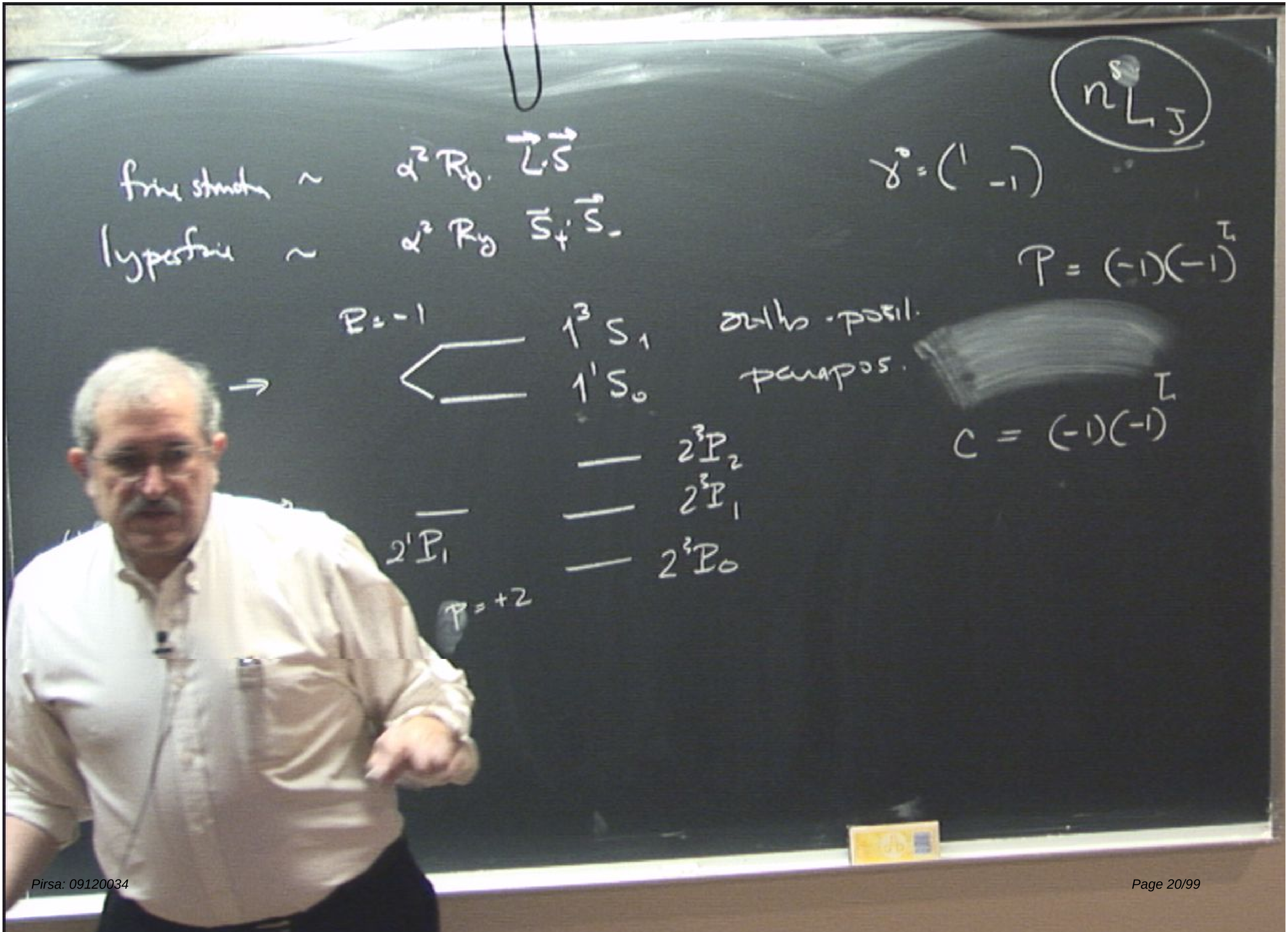
2^3P_2

$(1P)\ 2P \to$ 2^3P_1

2^1P_1

2^3P_0

$P = +2$


fine structure ~ α² Ry L·S
hyperfine ~ α² Ry S+·S-
γ° = (1 -1)
P = (-1)(-1)^L
C = (-1)(-1)^L
n^S L_J
P = -1
1³S₁ ortho-posit.
1¹S₀ parapos.
2³P₂
2³P₁
2¹P₁
2³P₀
P = +2

$n^{s}L_{J}$

fine structure $\sim \alpha^2 R_y\ \vec{L}\cdot\vec{S}$

hyperfine $\sim \alpha^2 R_y\ \vec{S}_+\cdot\vec{S}_-$

$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$

$P = (-1)(-1)^{L}$

$P = -1$

$1s \rightarrow$ 1^3S_1 ortho-posit.

1^1S_0 parapos.

spin 3

$C = (-1)(-1)^{L} \begin{cases} 1 \\ -1 \end{cases}$

spin 1

2^3P_2

$(1P)\ 2P \longrightarrow$ 2^3P_1

2^1P_1

2^3P_0

$P = +2$

e^-

$\frac{1}{n^2}$

μc^2

$\frac{1}{2} m_e$

fine structure $\sim \alpha^2 R_y \, \vec{L}\cdot\vec{S}$

hyperfine $\sim \alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$

$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$

$P =$

$P = -1$

$1s \rightarrow$ 1^3S_1 ortho-posit.

1^1S_0 para-pos.

$C = (-1$

2^3P_2

$(1P)\ 2P \rightarrow$ 2^1P_1 2^3P_1

2^3P_0

$P = +2$

$\{a_k^\dagger, b_p^\dagger\} = 0$

$$n^{S}L_J$$

fine structure ~ $\alpha^2 R_y \, \vec{L}\cdot\vec{S}$

hyperfine ~ $\alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$

$$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$$

$$P = (-1)(-1)^L$$

$P = -1$ $\quad C = -1$ $\quad 1^3S_1$ $\quad$ ortho-posit.

$1s \rightarrow$ $\quad 1^1S_0$ $\quad$ parapos.

$C = +$

spin 3

$$C = (-1)(-1)^L \begin{cases} 1 \\ -1 \end{cases}$$

spin 1

2^3P_2

$(1P)$ $\quad 2P \rightarrow$ $\quad 2^3P_1$

2^1P_1 $\quad 2^3P_0$

$P = +2$

$, b_p^\dagger\} = 0$

$n^{S}L_J$

fine structure $\sim \alpha^2 R_y \, \vec{L}\cdot\vec{S}$

hyperfine $\sim \alpha^2 R_y \, \vec{S}_+\cdot\vec{S}_-$

$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$

$P = (-1)(-1)^{L}$

$P=-1$ $C=-1$ 1^3S_1 ortho-posit.

$1s \rightarrow$ 1^1S_0 parapos.

$C=+$

spin 3

$C = (-1)(-1)^{L} \begin{cases} 1 \\ -1 \end{cases}$

spin 1

2^3P_2

$C=-$ 2^3P_1

$(1P)$ $2P \rightarrow$ 2^1P_1 2^3P_0

$P=+2$ $C=+$

$, b_p^\dagger\} = 0$

$n^{S}L_{J}$

fine structure $\sim \alpha^2 R_y \; \vec{L}\cdot\vec{S}$

hyperfine $\sim \alpha^2 R_y \; \vec{S}_+ \cdot \vec{S}_-$

$\gamma^0 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}$

$P = (-1)(-1)^{L}$

$1s \rightarrow$

$P = -1 \quad C = -1 \quad 1^3S_1$ ortho-posit.

$C = + \quad 1^1S_0$ parapos.

spin 3

$C = (-1)(-1)^{L} \begin{cases} 1 \\ -1 \end{cases}$

spin 1

$(1P) \quad 2P \rightarrow$

2^3P_2

$C = -$

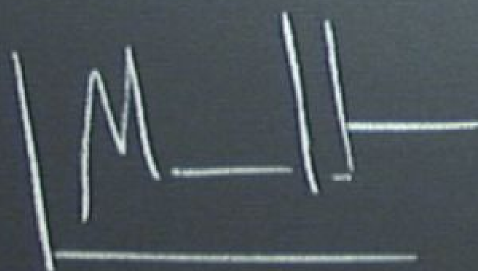
$2^1P_1 \qquad 2^3P_1$

2^3P_0

$P = +2 \qquad C = +$

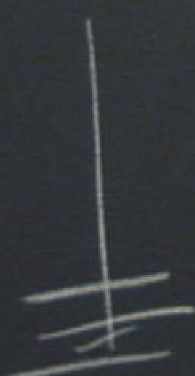
$, b_p^\dagger \} = 0$

γ $\quad C = -1$

R 

para $1^1S_0 \to 2\gamma$

ortho $1^3S_1 \to$



— mc^2 $\quad c\bar{c}$ charmonium

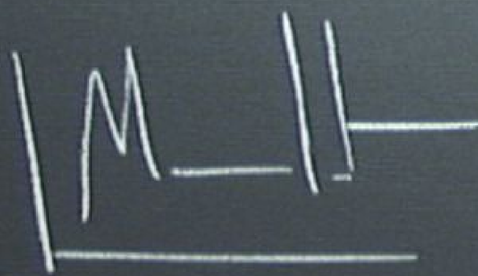
$b\bar{b}$ bottomonium

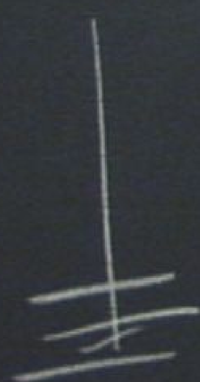
$\alpha mc = 1/a_0$ quarkonium

$\alpha^2 mc^2$

C

R





mc^2

$\alpha mc = 1/40$

$\alpha^2 mc^2$

$c\bar{c}$ charmonium

$b\bar{b}$ bottomonium

quarkonium

$\gamma \qquad C = -1$

Para $1^1S_0 \rightarrow 2\gamma$

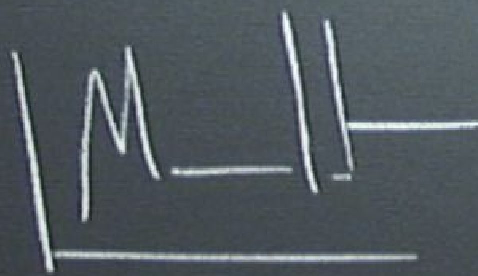
ortho $1^3S_1 \rightarrow 3\gamma$

Para ele $\quad \Gamma = \frac{1}{2}\alpha^5 mc^2$

$\tau = 1.2\times 10^{-10}$ sec

Orth. $\quad \Gamma = \frac{2}{9\pi}(\pi^2-9)\,\alpha^6 mc^2$

C

R 

$\gamma \quad C = -1$

Para $1^1S_0 \to 2\gamma$

ortho $1^3S_1 \to 3\gamma$

mc^2

$\alpha mc = 1/a_0$

$\alpha^2 mc^2$

$c\bar{c}$ charmonium

$b\bar{b}$ bottomonium

quarkonium

Para-ele $\Gamma = \frac{1}{2}\alpha^5 mc^2$

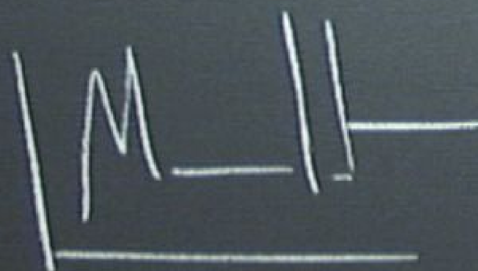
$\tau = 1.2\times10^{-10}$ sec

Orth. $\Gamma = \frac{2}{9\pi}(\pi^2-9)\,\alpha^6 mc^2$

C

$\tau = 1.4\times10^{-7}$ sec

R



$\leftarrow J = 1 \quad P = -1$
$C = -1$

C

$\gamma \quad C = -1$

Para $1^1S_0 \to 2\gamma$

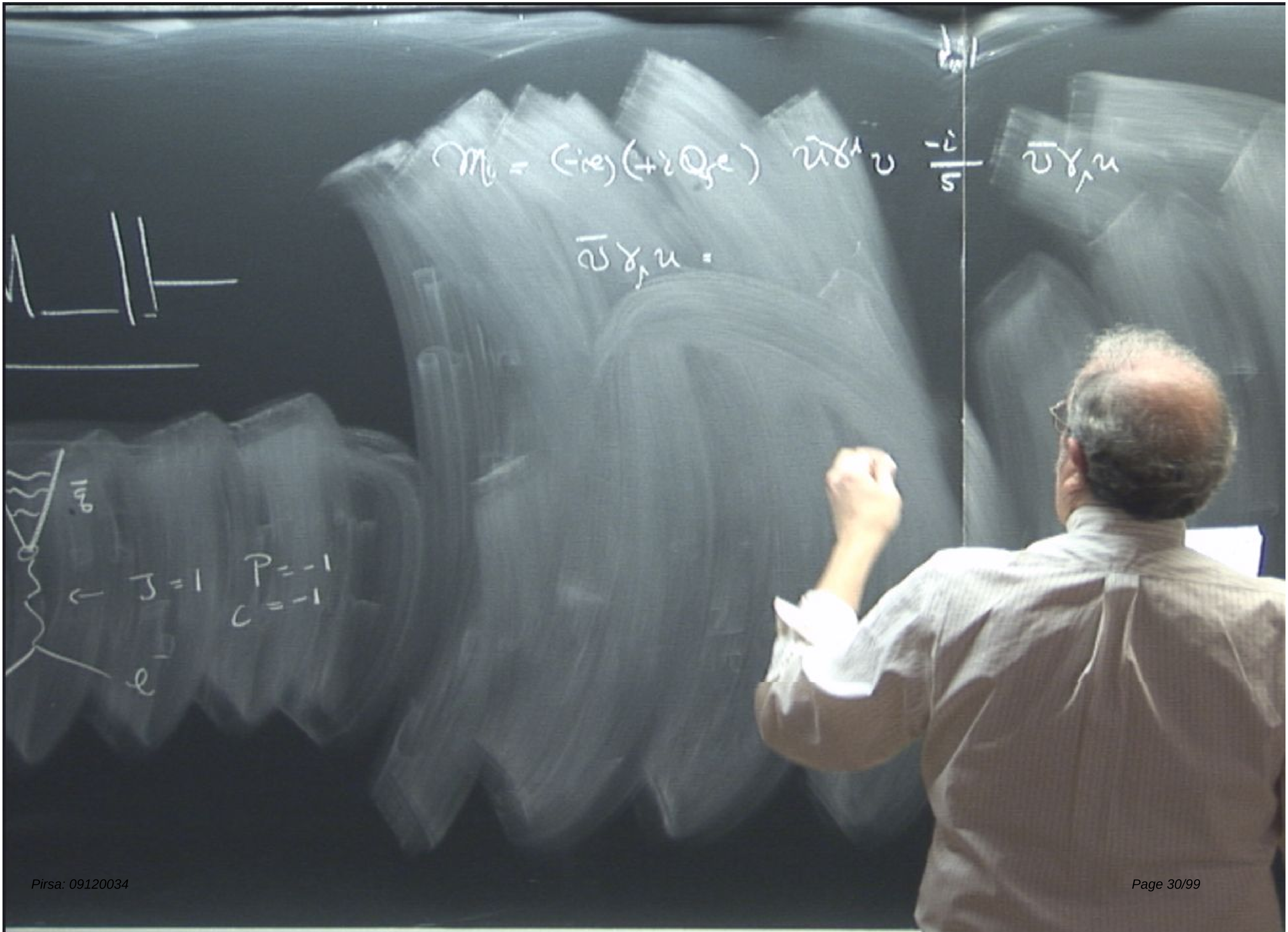
ortho $1^3S_1 \to 3\gamma$

Para ele $\Gamma = \frac{1}{2}\alpha^5 mc^2$

$\tau = 1.2\times 10^{-10}$ sec

Orth. $\Gamma = \frac{2}{9\pi}(\pi^2 - 9)\,\alpha^6 mc^2$

$\tau = 1.4\times 10^{-7}$ sec



M = (-ie)(+iQ e) v̄γ^μ v -i/s ūγ_μ u
v̄γ_μ u =
J = 1
P = -1
C = -1
e⁻

$$\mathcal{M}_i = (-ie)(+iQ_q e)\ \bar{u}\gamma^\mu v\ \frac{-i}{s}\ \bar{v}\gamma_\mu u$$

$$\bar{v}\gamma_\mu u = \sqrt{s}\,\sqrt{2}\quad \varepsilon^\mu_{L,R}$$

$\leftarrow$ $J=1$ $P=-1$

$C=-1$

$$\mathcal{M}_i = (-ie)(+iQ_q e)\, \bar{u}\gamma^\mu v \, \frac{-i}{s} \, \bar{v}\gamma_\mu u$$

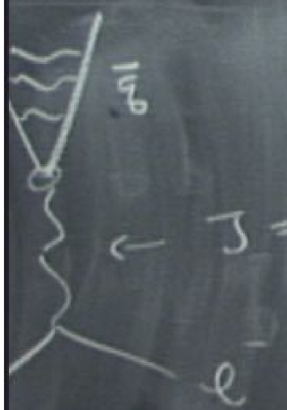
$$\bar{v}\gamma_\mu u = \sqrt{s}\,\sqrt{2} \quad \epsilon^\mu_{L,R}$$

$\leftarrow$ $J = 1$ $P = -1$ $C = -1$

$$\mathcal{M} = (-ie)(+iQ_f e)\, \bar{u}\gamma^\mu v \, \frac{-i}{s} \, \bar{v}\gamma_\mu u$$

$$\bar{v}\gamma_\mu u = \sqrt{s}\,\sqrt{2}\ \ \varepsilon^\mu_{L,R}$$

$$u = \sqrt{m}\begin{pmatrix}1\\1\end{pmatrix}\xi \qquad v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$$



$\leftarrow J = 1 \quad P = -1$
$C = -1$

$$\mathcal{M}_1 = (-ie)(+iQ_f e)\, \bar{v}\gamma^\mu v \, \frac{-i}{s} \, \bar{v}\gamma_\mu u$$

$$\bar{v}\gamma_\mu u = \sqrt{s}\,\sqrt{2}\;\xi^\mu_{L,R}$$

$$u = \sqrt{m}\begin{pmatrix}1\\1\end{pmatrix}\xi \qquad v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$$

$$\bar{v}\gamma^\mu u = v^\dagger \begin{pmatrix} & \bar{\sigma}^\mu \\ \sigma^\mu & \end{pmatrix} u$$

$$= \left(0,\; -m\, \xi^\dagger \vec{\sigma} \xi\right)$$

$J = 1$ $P = -1$
$C = -1$

e^-

$) \ \underline{\bar{u}\gamma^{\mu}} v \ \frac{-i}{s} \ \bar{v}\gamma_{\mu} u$

$\sqrt{s}\ \sqrt{2} \quad \varepsilon^{\mu}_{L,R}$

$) \ \xi \qquad v = \sqrt{m} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \xi$

$v^{+} \begin{pmatrix} \bar{\sigma}^{\mu} & \\ & \sigma^{\mu} \end{pmatrix} u$

$(0, -m \ \xi^{+} \vec{\sigma} \xi)$

$\mathcal{M} = i Q_f e^2 \frac{\sqrt{2}\sqrt{s}\ m}{s} \ \xi^{+} \vec{\sigma} \ \xi$

$) \ \bar{u}\gamma^\mu v \ \frac{-i}{s} \ \bar{v}\gamma_\mu u$

$\mathcal{M} = i Q_q e^2 \ \frac{\sqrt{2}\sqrt{s}\ m}{s} \ \xi^\dagger_{\bar q}\vec\sigma\cdot\vec\epsilon\ \xi_q$

$\sqrt{s}\ \sqrt{2} \qquad \epsilon^\mu_{L,R}$

$)\ \xi \qquad v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$

$v^\dagger\begin{pmatrix}\bar\sigma^\mu & \\ & \sigma^\mu\end{pmatrix}u$

$\left(0,\ -m\ \xi^\dagger\vec\sigma\xi\right)$

$) \; \bar{u}\gamma^\mu v \; \frac{-i}{s} \; \bar{v}\gamma_\mu u$ $\qquad \mathcal{M} = i Q_q e^2 \, \frac{\sqrt{2}\sqrt{s}\; m}{s} \; \xi^\dagger_{\bar q}\, \vec{\sigma}\cdot\underbrace{\vec{\epsilon}_{L,R}}\, \xi_q$

$\sqrt{s}\;\sqrt{2} \qquad \epsilon^\mu_{L,R}$ $\qquad (\sqrt{2}\,\sigma^+ , \; \sqrt{2}\,\sigma^-)$

$) \; \xi \qquad v = \sqrt{m}\begin{pmatrix} 1 \\ -1 \end{pmatrix}\xi$

$v^\dagger \begin{pmatrix} \bar{\sigma}^\mu & \\ & \sigma^\mu \end{pmatrix} u$

$(0 , \; -m \;\; \xi^\dagger \vec{\sigma}\, \xi)$

$\bar{v}\gamma^\mu v \; \frac{-i}{s} \; \bar{v}\gamma_\mu u$

$\mathcal{M} = i Q_q e^2 \frac{\sqrt{2}\sqrt{s}\, m}{s} \; \xi_q^{\dagger} \vec{\sigma} \cdot \vec{\varepsilon}_{L,R}\, \xi_q$

$\sqrt{s}\; \sqrt{2} \quad \varepsilon^\mu_{L,R}$

$(\sqrt{2}\sigma^+ , \sqrt{2}\sigma^-)$

$v = \sqrt{m} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \xi$

$B \to e^+ e^-$

$v^\dagger \begin{pmatrix} \bar{\sigma}^\mu & \\ & \sigma^\mu \end{pmatrix} u$

$(0, -m \; \xi^\dagger \vec{\sigma} \xi)$

$$\bar{u}\gamma^\mu v \quad \frac{-i}{s} \quad \bar{v}\gamma_\mu u$$

$$\sqrt{s}\,\sqrt{2} \qquad \varepsilon^\mu_{L,R}$$

$$v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$$

$$v^\dagger\begin{pmatrix}\bar{\sigma}^\mu & \\ & \sigma^\mu\end{pmatrix}u$$

$$\left(0,\ -m\ \xi^\dagger\vec{\sigma}\xi\right)$$

$$\mathcal{M} = iQ_q e^2\,\frac{\sqrt{2}\sqrt{s}\,m}{s}\,\xi^\dagger_{\bar{q}}\,\vec{\sigma}\cdot\underbrace{\vec{\varepsilon}_{L,R}}\,\xi_q$$

$$(\sqrt{2}\,\sigma^+,\ \sqrt{2}\,\sigma^-)$$

$$\underbrace{B} \rightarrow e^+e^-$$

$$|B\rangle = \int\frac{d^3k}{(2\pi)^3}\,\psi(k)\,\Sigma_{ab}$$

$) \quad \underline{\bar{u}\gamma^\mu} v \quad \frac{-i}{s} \quad \bar{v}\gamma_\mu u$

$\sqrt{s}\ \sqrt{2} \qquad \varepsilon^\mu_{L,R}$

$) \ \xi \qquad v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$

$v^+ \begin{pmatrix}\bar{\sigma}^\mu & \\ & \sigma^\mu\end{pmatrix} u$

$(0, -m \quad \xi^\dagger \vec{\sigma}\, \xi)$

$$\mathcal{M} = iQ_q e^2 \frac{\sqrt{2}\sqrt{s}\ m}{s}\ \xi^\dagger_{\bar{q}}\, \vec{\sigma} \cdot \underbrace{\vec{\varepsilon}_{L,R}}\, \xi_q$$

$(\sqrt{2}\sigma^+ , \sqrt{2}\sigma^-)$

$\underbrace{B} \longrightarrow e^+e^-$

$$|B\rangle = \int \frac{d^3k}{(2\pi)^3}\, \psi(k)\, \Sigma_{ab}$$

$$|\bar{q}(-\vec{k}, a)\, q(k, b)\rangle$$

$\bar{v}\gamma^\mu v \quad \frac{-i}{s} \quad \bar{v}\gamma_\mu u$

$\sqrt{s}\ \sqrt{2} \quad \varepsilon^\mu_{L,R}$

$\xi \quad v = \sqrt{m}\begin{pmatrix} 1 \\ -1 \end{pmatrix}\xi$

$v^+\begin{pmatrix} \bar{\sigma}^\mu & \\ & \sigma^\mu \end{pmatrix} u$

$(0, -m \quad \xi^+ \vec{\sigma}\xi)$

$\mathcal{M} = i Q_q e^2 \frac{\sqrt{2}\sqrt{s}\ m}{s} \xi^+_{\bar{q}} \vec{\sigma} \cdot \underbrace{\vec{\varepsilon}_{L,R}} \xi_q$

$(\sqrt{2}\sigma^+, \sqrt{2}\sigma^-)$

$\underline{B} \to e^+e^-$

$|B\rangle = \sqrt{2M}\int\frac{d^3k}{(2\pi)^3}\ \psi(k)\ \Sigma_{ab}$

$\frac{1}{\sqrt{2m}\ 2m} \left| \bar{q}(-\vec{k}, a)\ q(k, b) \right\rangle$

$M \approx 2m$

$\underline{\bar{u}\gamma^\mu v} \; \frac{-i}{s} \; \bar{v}\gamma_\mu u$

$\sqrt{s}\,\sqrt{2} \qquad \epsilon^\mu_{L,R}$

$\xi \qquad v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$

$v^\dagger \begin{pmatrix}\bar{\sigma}^\mu & \\ & \sigma^\mu\end{pmatrix} u$

$\left(0,\; -m\; \xi^\dagger \vec{\sigma}\, \xi\right)$

$$i\mathcal{M} = iQ_q e^2 \,\frac{\sqrt{2}\sqrt{s}\; m}{s}\; \xi^\dagger_{-q}\,\underbrace{\vec{\sigma}\cdot\vec{\epsilon}_{L,R}}\,\xi_q$$

$$(\sqrt{2}\sigma^+ ,\; \sqrt{2}\sigma^-)$$

$$\underbrace{B} \longrightarrow e^+e^-$$

$$|B\rangle = \sqrt{2M}\int\frac{d^3k}{(2\pi)^3}\,\psi(k)\sum_{ab}\; \frac{1}{\sqrt{2m}\;2m}\,|q(-\vec{k},a)\, q(k,b)\rangle$$

$$M \approx 2m$$

$\bar v \gamma^\mu v \quad \frac{-i}{s} \quad \bar v \gamma_\mu u$

$\sqrt{s}\ \sqrt{2} \quad \varepsilon^\mu_{L,R}$

$\xi \qquad v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$

$v^+ \begin{pmatrix}\bar\sigma^\mu & \\ & \sigma^\mu\end{pmatrix} u$

$\left(0,\ -m\ \xi^+ \vec\sigma \xi\right)$

$\Sigma = 1 \qquad (\vec n \vec\sigma)$

spin 1 spin 3

$$\mathcal{M} = iQ_q e^2 \frac{\sqrt{2}\sqrt{s}\, m}{s}\ \xi^+_{\bar q}\, \underbrace{\vec\sigma \cdot \vec\varepsilon_{L,R}}\, \xi_q$$

$(\sqrt{2}\sigma^+,\ \sqrt{2}\sigma^-)$

$\underline{B} \to e^+e^-$

$$|B\rangle = \sqrt{2M}\int \frac{d^3k}{(2\pi)^3}\, \psi(k)\, \Sigma_{ab}\, \frac{1}{\sqrt{2m}\ 2m}\, |q(-\vec k, a)\, \bar q(k, b)\rangle$$

$M \approx 2m$

$\bar{u}\gamma^\mu v \quad \frac{-i}{s} \quad \bar{v}\gamma_\mu u$

$\sqrt{s}\ \sqrt{2} \quad \varepsilon^\mu_{L,R}$

$v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$

ξ

$v^+\begin{pmatrix}\vec{\sigma}^\mu & \\ & \sigma^\mu\end{pmatrix}u$

$(0,\ -m\ \ \xi^+\vec{\sigma}\xi)$

$\Sigma = 1 \quad (\vec{n}\vec{\sigma})$

spin 1 $\quad$ spin 3

$\mathcal{M} = iQ_q e^2 \frac{\sqrt{2}\sqrt{s}\ m}{s}\ \xi^+_{\bar q}\,\vec{\sigma}\cdot\underbrace{\vec{\varepsilon}_{L,R}}\,\xi_q$

$(\sqrt{2}\sigma^+,\ \sqrt{2}\sigma^-)$

$\underbrace{B} \to e^+e^-$

$|B\rangle = \sqrt{2M}\int\frac{d^3k}{(2\pi)^3}\,\psi(k)\,\Sigma_{ab} \quad \delta_{ij}$

$\frac{1}{\sqrt{2m}\,2m}\,|\bar{q}_i(-\vec{k},a)\,q_j(k,b)\rangle$

$M \approx 2m$

$\bar{v}\gamma^\mu v \quad \frac{-i}{s} \quad \bar{v}\gamma_\mu u$

$\sqrt{s}\,\sqrt{2} \quad \varepsilon^\mu_{L,R}$

$v = \sqrt{m}\begin{pmatrix}1\\-1\end{pmatrix}\xi$

ξ

$v^+\begin{pmatrix}\bar{\sigma}^\mu & \\ & \sigma^\mu\end{pmatrix}u$

$(0, \; -m \; \xi^+\vec{\sigma}\xi)$

$\Sigma = 1 \quad (\vec{n}\vec{\sigma})$

spin 1 $\quad$ spin 3

$\mathcal{M} = iQ_q e^2 \frac{\sqrt{2}\sqrt{s}\,m}{s}\,\xi^+_{\bar{q}}\vec{\sigma}\cdot\underbrace{\vec{\varepsilon}_{L,R}}\,\xi_q$

$(\sqrt{2}\sigma^+, \sqrt{2}\sigma^-)$

$\underbrace{B} \longrightarrow e^+e^-$

$|B\rangle = \sqrt{2M}\int\frac{d^3k}{(2\pi)^3}\,\psi(k)\,\Sigma_{ab}\,\frac{1}{\sqrt{3}}\delta_{ij}$

$\frac{1}{\sqrt{2m}\,2m}\,|\bar{q}_i(-\vec{k},a)\,q_j(k,b)\rangle$

$M \approx 2m$

$\bar{v}\gamma^\mu v \quad \frac{-i}{s} \quad \bar{v}\gamma_\mu u$

$\sqrt{s}\ \sqrt{2} \quad \varepsilon^\mu_{L,R}$

$\mathcal{M} = i Q_q e^2 \frac{\sqrt{2}\sqrt{s}\, m}{s} \xi^\dagger_{\bar{q}} \vec{\sigma} \cdot \underbrace{\vec{\varepsilon}_{L,R}} \xi_q$

$(\sqrt{2}\sigma^+ , \sqrt{2}\sigma^-)$

$\xi \qquad v = \sqrt{m} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \xi$

$\underbrace{B} \longrightarrow e^+e^-$

$v^\dagger \begin{pmatrix} \bar{\sigma}^\mu & \\ & \sigma^\mu \end{pmatrix} u$

$|B\rangle = \sqrt{2M} \int \frac{d^3k}{(2\pi)^3} \psi(k) \Sigma_{ab} \frac{1}{\sqrt{3}} \delta_{ij} \frac{1}{\sqrt{2m}\, 2m} |q_i(-\vec{k}, a)\, \bar{q}_j(k, b)\rangle$

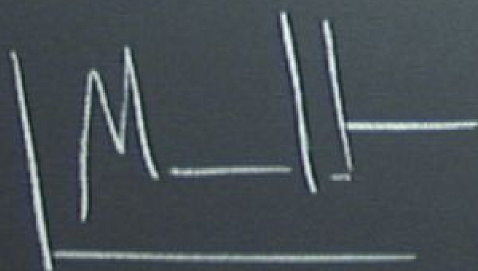
$(0, -m \ \xi^\dagger \vec{\sigma} \xi)$

$(\vec{n}\vec{\sigma})$

$\Sigma = 1$

spin 1 $\qquad$ spin 3

$M \approx 2m$

R 

$$\mathcal{M}(B \to e^+e^-) \sim k\left[\Sigma\,(\vec{\sigma}\cdot\vec{\xi}_f)\right]$$

$$= \begin{cases} 0 & \text{spin } 1 \\ 2\vec{n}\cdot\vec{\varepsilon} & \end{cases}$$

$$\mathcal{M} = (-ie)(+iQ_f e)\ \bar{v}\gamma^\mu v\ \frac{-i}{s}$$

$$\bar{v}\gamma_\mu u = \sqrt{s}\,\sqrt{2}\quad \varepsilon^\mu_{L,R}$$

$$u = \sqrt{m}\begin{pmatrix}1\\1\end{pmatrix}\xi \qquad v =$$

$$\bar{v}\gamma^\mu u = v^\dagger\left(\bar{\sigma}^\mu\ \ \sigma^\mu\right)$$

$$= (0, -m$$

$$\Sigma$$

$$\mathcal{M}_1 = (-ie)(+iQ_f e)\ \bar{v}\gamma^\mu v\ \frac{-i}{s}\ \bar{v}$$

$$\bar{v}\gamma_\mu u = \sqrt{s}\sqrt{2}\quad \varepsilon^\mu_{L,R}$$

$$u = \sqrt{m}\begin{pmatrix}1\\1\end{pmatrix}\xi \qquad v = \sqrt{m}\,($$

$$\mathcal{M}(B\to e^+e^-) \sim k\left[\Sigma\,(\bar{\sigma}\cdot\bar{\varepsilon}_{L,R})\right] = \begin{cases} 0 & \text{spin 1} \\ \sqrt{2}\,\vec{n}\cdot\vec{\varepsilon} & \text{spin 3} \end{cases}$$

$$\bar{v}\gamma^\mu u = v^\dagger\begin{pmatrix} & \bar{\sigma}^\mu \\ \sigma^\mu & \end{pmatrix}u = (0,\ -m\ \ \xi^\dagger$$

$$\Sigma = \frac{1}{\sqrt{2}}$$

$$\mathcal{M}_1 = (-ie)(+iQ_f e)\ \bar{v}\gamma^\mu v\ \frac{-i}{s}\ \bar{v}$$

$$\bar{v}\gamma_\mu u = \sqrt{s}\sqrt{2}\quad \xi^\mu_{L,R}$$

$$u = \sqrt{m}\begin{pmatrix}1\\1\end{pmatrix}\xi \qquad v = \sqrt{m}\ ($$

$$\mathcal{M}(B\to e^+e^-) \sim k[\Sigma(\vec{\sigma}\cdot\vec{\xi}_f)]$$

$$= \begin{cases} 0 & \text{spin singlet } s=0 \\ \sqrt{2}\,\vec{n}\cdot\vec{\Sigma} & \text{spin triplet } s=1 \end{cases}$$

$$\bar{v}\gamma^\mu u = v^\dagger(\bar{\sigma}^\mu\ \ \sigma^\mu)u$$

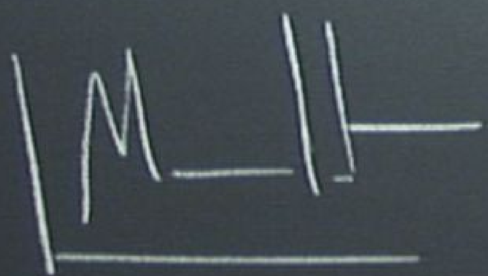
$$= (0,\ -m\ \ \xi^\dagger$$

$$\Sigma = \frac{1}{\sqrt{2}}$$

$$2ie^2 Q_f \sqrt{\frac{2}{M}} \cdot \sqrt{3} \left(\int \frac{d^3k}{(2\pi)^3} \psi(k) \right)$$

$\psi(r=0)$

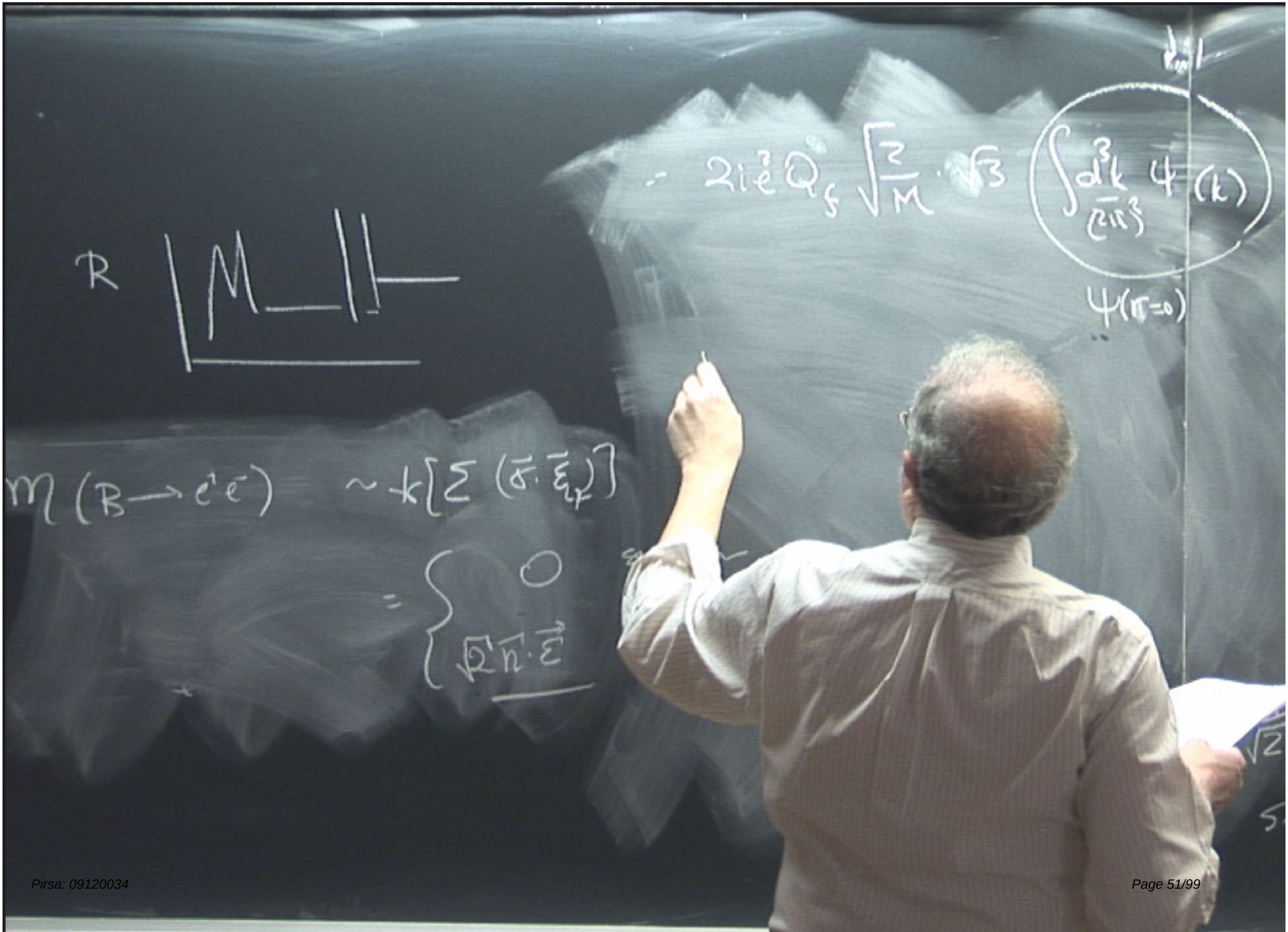
R



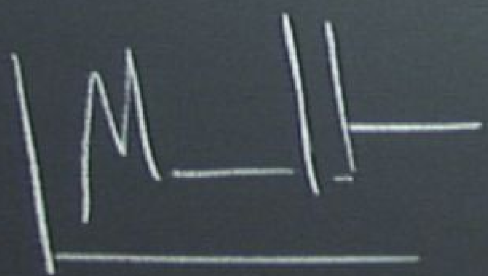
$$\mathcal{M}(B \to e^+e^-) \sim k[\Sigma (\vec\sigma \cdot \vec\varepsilon_\gamma)]$$

$$= \begin{cases} 0 & \text{spin sp} \\ \sqrt{2}\,\vec n\cdot\vec\varepsilon & \text{spin tr},\ S=1 \end{cases}$$

$\Sigma = \sqrt{2}$


R
$\mathcal{M}(B \to e^+e^-)$
$\sim k[\Sigma(\vec{\sigma}\cdot\vec{\xi}_f)]$
$= \begin{cases} 0 \\ \sqrt{2}\,\vec{n}\cdot\vec{\varepsilon} \end{cases}$
$2ie^2 Q_f \sqrt{\frac{2}{M}} \cdot \sqrt{3} \int \frac{d^3k}{(2\pi)^3} \psi(k)$
$\psi(r=0)$

R



$$- 2ie^2 Q_f \sqrt{\frac{2}{M}} \cdot \sqrt{3} \int \frac{d^3k}{(2\pi)^3} \psi(k)$$

$\psi(r=0)$

$|\mathcal{M}|^2$

$$\mathcal{M}(B \to e^+e^-) \sim k[\Sigma (\vec{\sigma}\cdot\vec{\epsilon}_\gamma)]$$

$$= \begin{cases} 0 & \text{spin sp} \\ \sqrt{2}\,\vec{n}\cdot\vec{\epsilon} & \text{sp tr}\ \ s=1 \end{cases}$$

$\Sigma = \sqrt{2}$

$$-2ie^2 Q_s \sqrt{\frac{2}{M}} \cdot \sqrt{3} \int \frac{d^3k}{(2\pi)^3} \psi(k) \quad \vec{n}\cdot\vec{\varepsilon}^{\,*} \qquad \mathcal{M} = iQ_s e^2$$

$$\psi(r=0)$$

$$|\mathcal{M}|^2 = \frac{3 \cdot 8 e^4 Q_s^2}{M} \psi(0) \quad (\vec{n}\cdot\vec{\varepsilon})^2$$

$$(\vec{\sigma}\cdot\vec{\xi}_\gamma)]$$

$$\Gamma(B \to e^+ e^-) = \frac{1}{2M} \quad \frac{1}{8\pi}$$

0 spin spin

$\vec{\sigma}\,\vec{n}\cdot\vec{\varepsilon}$ spin $s=1$

$$\Sigma = \frac{1}{\sqrt{2}} \mathbb{1} \qquad \left(\frac{\vec{n}\cdot\vec{\sigma}}{\sqrt{2}}\right)$$

spin 1 spin 3

$$- 2ie^2 Q_f \sqrt{\frac{2}{M}} \cdot \sqrt{3} \left(\int \frac{d^3k}{(2\pi)^3} \psi(k) \right) \vec{n}\cdot\vec{\varepsilon}^{\,*}$$

$$\mathcal{M} = i Q_f e^2 \frac{\sqrt{2}\sqrt{5}}{5}$$

$$\psi(r=0)$$

$$|\mathcal{M}|^2 = \frac{3 \cdot 8 e^4 Q_f^2}{M} |\psi(0)|^2 \, |\vec{n}\cdot\vec{\varepsilon}|^2$$

$$\Gamma(B \to e^+ e^-) = \frac{1}{2M} \frac{1}{8\pi} \frac{8 \cdot 3}{M} Q_f^2 |\psi(0)|^2 \frac{1}{3} \sum_n |\vec{n}\cdot\vec{\varepsilon}|^2$$

spin spin

spin ½

$s = 1$

$$\Sigma = \frac{1}{\sqrt{2}} \, 1 \qquad \left(\frac{\vec{n}\cdot\vec{\sigma}}{\sqrt{2}} \right)$$

spin 1 spin 3

$\sqrt{7m}$

M

$$-\ 2ie^2 Q_f \sqrt{\frac{2}{M}} \cdot \sqrt{3} \int \frac{d^3k}{(2\pi)^3} \psi(k) \quad \vec{n}\cdot\vec{\varepsilon}^{\,*} \qquad \mathcal{M} = i Q_f e^2 \frac{\sqrt{2}\sqrt{5}}{5}$$

$$\psi(r=0)$$

$$|\mathcal{M}|^2 = \frac{3 \cdot 8 e^4 Q_f^2}{M} |\psi(0)|^2 \, |\vec{n}\cdot\vec{\varepsilon}|^2$$

$$\Gamma(B \to e^+ e^-) = \frac{1}{2M} \frac{1}{8\pi} \frac{8 \cdot 3}{M} Q_f^2 |\psi(0)|^2 \Big(\frac{1}{3} \sum_n |\vec{n}\cdot\vec{\varepsilon}|^2 \cdot 2 \Big)$$

$$\frac{2}{3}$$

spin spin

$$= \frac{16\pi\alpha^2}{M^2} |\psi(0)|^2 Q_f^2$$

spin spin

$s=1$

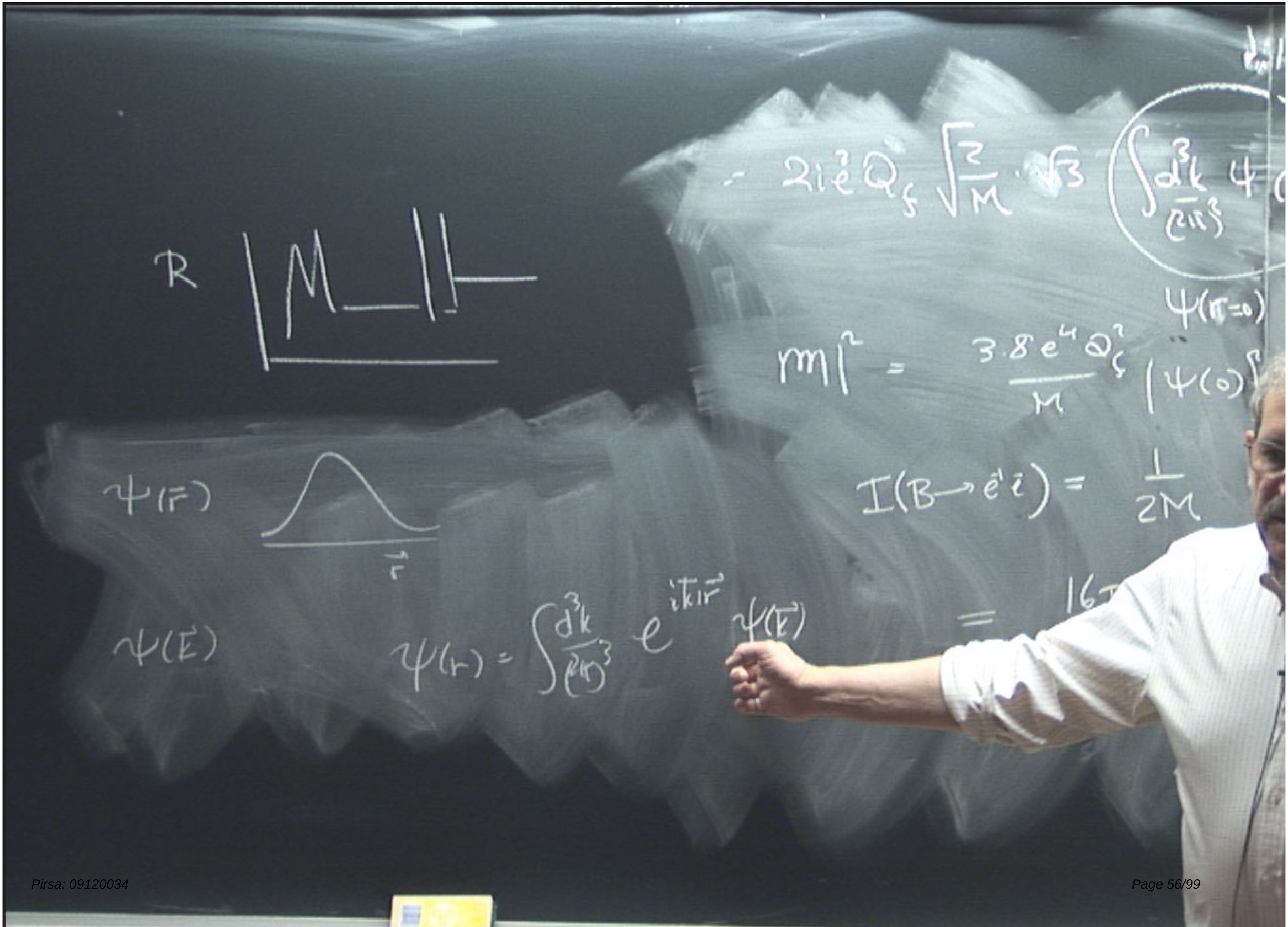
$$\frac{1}{\sqrt{2m}\,2m}$$

$$\left(\frac{\vec{n}\cdot\vec{\sigma}}{\sqrt{2}}\right)$$

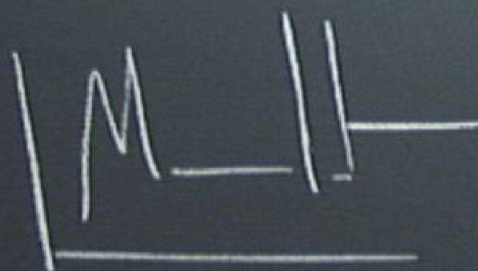
$$\sum = \frac{1}{\sqrt{2}} 1$$

spin 1 spin 3

M


R
ψ(r⃗)
r⃗
ψ(k⃗)
ψ(r) = ∫ d³k/(2π)³ e^{ik⃗·r⃗} ψ(k⃗)
2ie³Q_f √(2/M) · √3 (∫ d³k/(2π)³ ψ
ψ(r=0)
|m|² = 3·8e⁴Q_f²/M |ψ(0)|
Γ(B → e⁺e⁻) = 1/2M
= 16π

R

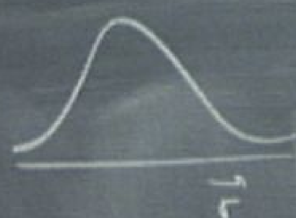


$$2ie^3 Q_f \sqrt{\frac{2}{M}} \cdot \sqrt{3} \left(\int \frac{d^3k}{(2\pi)^3} \psi (\right.$$

$\psi(\vec r = 0)$

$$|m|^2 = \frac{3 \cdot 8 e^4 Q_f^2}{M} |\psi(0)|^2$$

$\psi(\vec r)$



$$\Gamma(B \to e^+ e^-) = \frac{1}{2M}$$

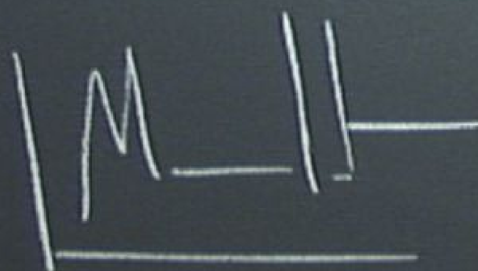
$\psi(\vec k)$

$$\psi(r) = \int \frac{d^3k}{(2\pi)^3} e^{i\vec k \cdot \vec r} \psi(\vec k)$$

$$= \frac{16\pi\alpha^2}{M^2} |\psi($$

Σ

R

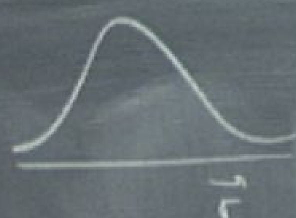


$$= 2ie^2 Q_f \sqrt{\frac{2}{M}} \cdot \sqrt{3} \left(\int \frac{d^3k}{(2\pi)^3} \psi \right.$$

$\psi(\vec{r}=0)$

$$|m|^2 = \frac{3.8\, e^4 Q_f^2}{M} |\psi(0)|^2$$

$\psi(\vec{r})$



$$\Gamma(B \to e^+ e^-) = \frac{1}{2M}$$

$$\psi(r) = \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\cdot\vec{r}} \psi(\vec{k})$$

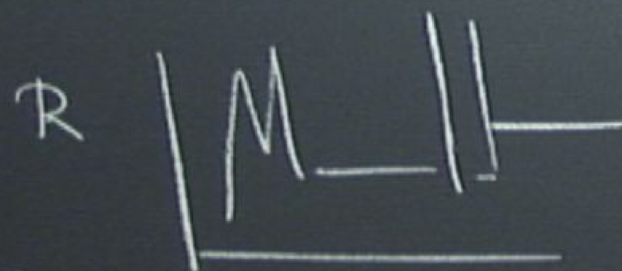
$\psi(\vec{k})$

$$= \frac{16\pi\alpha^2}{M^2} |\psi(0)|^2$$

Σ

$$-2ie^3 Q_f \sqrt{\frac{2}{M}}\cdot\sqrt{3}\left(\int\frac{d^3k}{(2\pi)^3}\,\psi(\right.$$

$$\psi(r=0)$$



$$|m|^2 = \frac{3\cdot 8\, e^4 Q_f^2}{M}\,|\psi(0)|^2$$

n^3S_1

$$\Gamma(B\to e^+e^-) = \frac{16\pi\alpha^2}{M}\,|\psi(0)|^2\, Q_f^2$$

$$\Gamma(B\to e^+e^-) = \frac{1}{2M}$$

$$(e^+e^-\to B) =$$

$$= \frac{16\pi\alpha^2}{M^2}\,|\psi($$

$$\Sigma$$

R

n^3S_1

$$\Gamma(B \to e^+e^-) = \frac{16\pi\alpha^2}{M} |\psi(0)|^2 Q_f^2$$

$$\Gamma(e^+e^- \to B) =$$

$$\int \frac{d^3k}{(2\pi)^3} \frac{1}{2M}$$

$\psi(\ldots)$

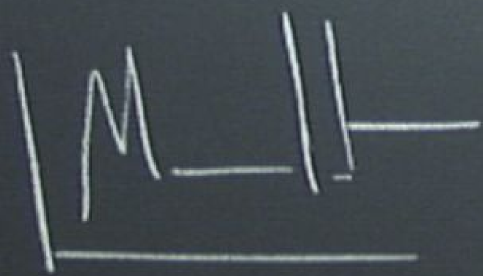
$$|m|^2 = \frac{e^4 Q_f^2}{\ldots} |\psi(0)|^2$$

$$\Gamma(B \to \ldots) \quad \frac{1}{4}$$

$$= \frac{16\ldots}{M^2}$$

Σ

$$\int \frac{d^3k}{(2\pi)^3} \frac{1}{2E} (2\pi)^4 \delta(k_1 + k_2 - k)$$

R 

$\psi(\ldots)$

$$|\mathcal{M}|^2 = \frac{3 \cdot 8 e^4 Q_q^2}{M} |\psi(0)|^2$$

n^3S_1

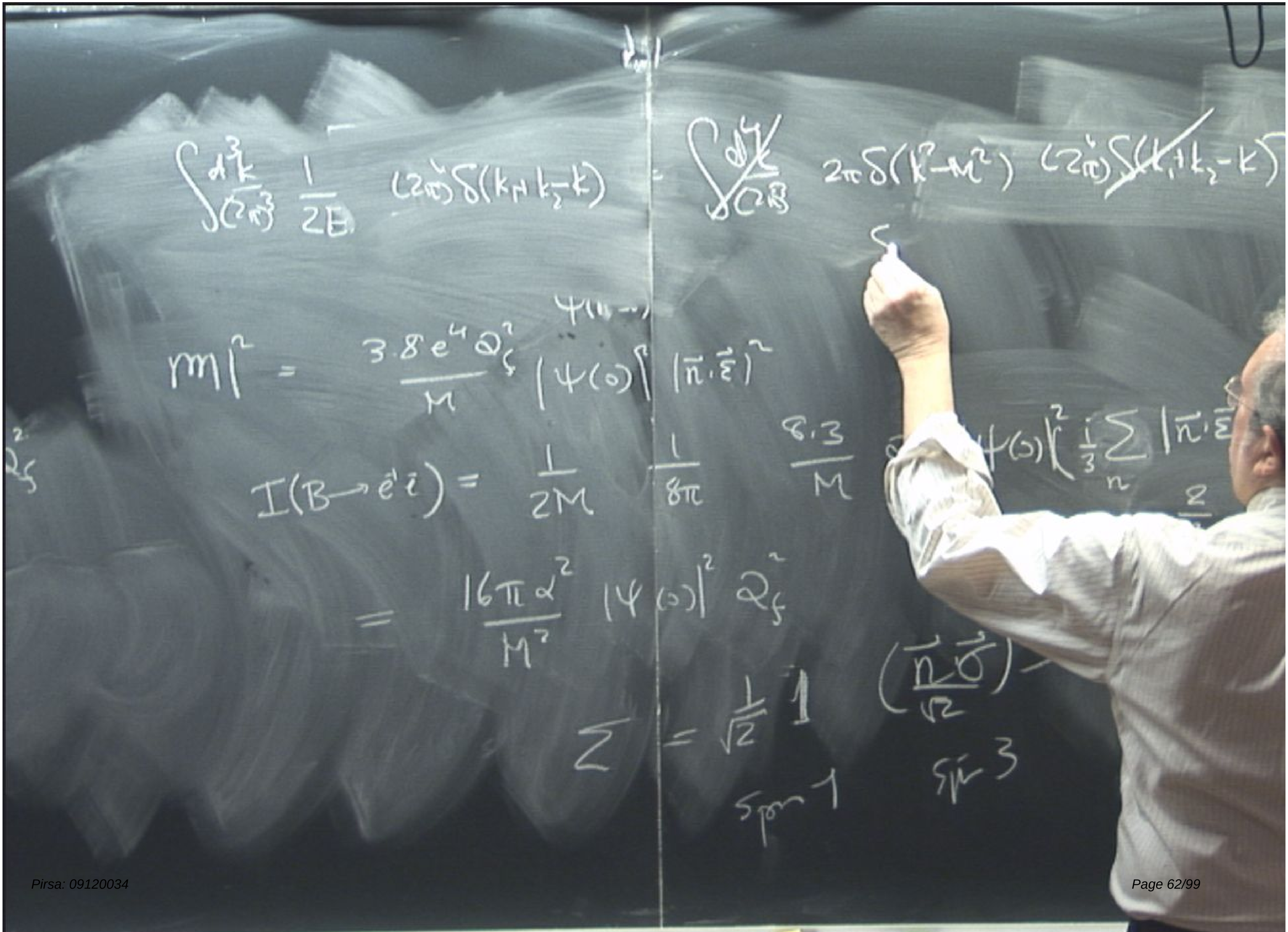
$$\Gamma(B \to e^+e^-) = \frac{16\pi\alpha^2}{M} |\psi(0)|^2 Q_q^2$$

$$\Gamma(B \to e^+e^-) = \frac{1}{2M}$$

$$\Gamma(e^+e^- \to B) =$$

$$= \frac{16\pi\alpha^2}{M^2} |\psi(0$$

Σ


$\int \frac{d^3k}{(2\pi)^3} \frac{1}{2E} (2\pi)^4 \delta(k_1+k_2-k) = \int \frac{d^4k}{(2\pi)^3} 2\pi\delta(k^2-M^2)\, (2\pi)^4 \delta(k_1+k_2-k)$
$|\mathcal{M}|^2 = \frac{3 \cdot 8 e^4 Q_f^2}{M} |\psi(0)|^2 |\vec{n}\cdot\vec{\varepsilon}|^2$
$\Gamma(B \to e^+e^-) = \frac{1}{2M} \frac{1}{8\pi} \frac{8 \cdot 3}{M} |\psi(0)|^2 \frac{1}{3}\sum_n |\vec{n}\cdot\vec{\varepsilon}|$
$= \frac{16\pi\alpha^2}{M^2} |\psi(0)|^2 Q_f^2$
$\Sigma = \frac{1}{\sqrt{2}} \mathbb{1} \quad \left(\frac{\vec{n}\cdot\vec{\sigma}}{\sqrt{2}}\right)$
spin 1
spin 3

$$\int \frac{d^3k}{(2\pi)^3} \frac{1}{2E} (2\pi)^4 \delta(k_1 + k_2 - k) = \int \frac{d^4k}{(2\pi)^3} 2\pi\delta(k^2 - M^2) (2\pi)^4 \cancel{\delta(k_1 + k_2 - k)}$$

$$\delta(s - M^2)$$

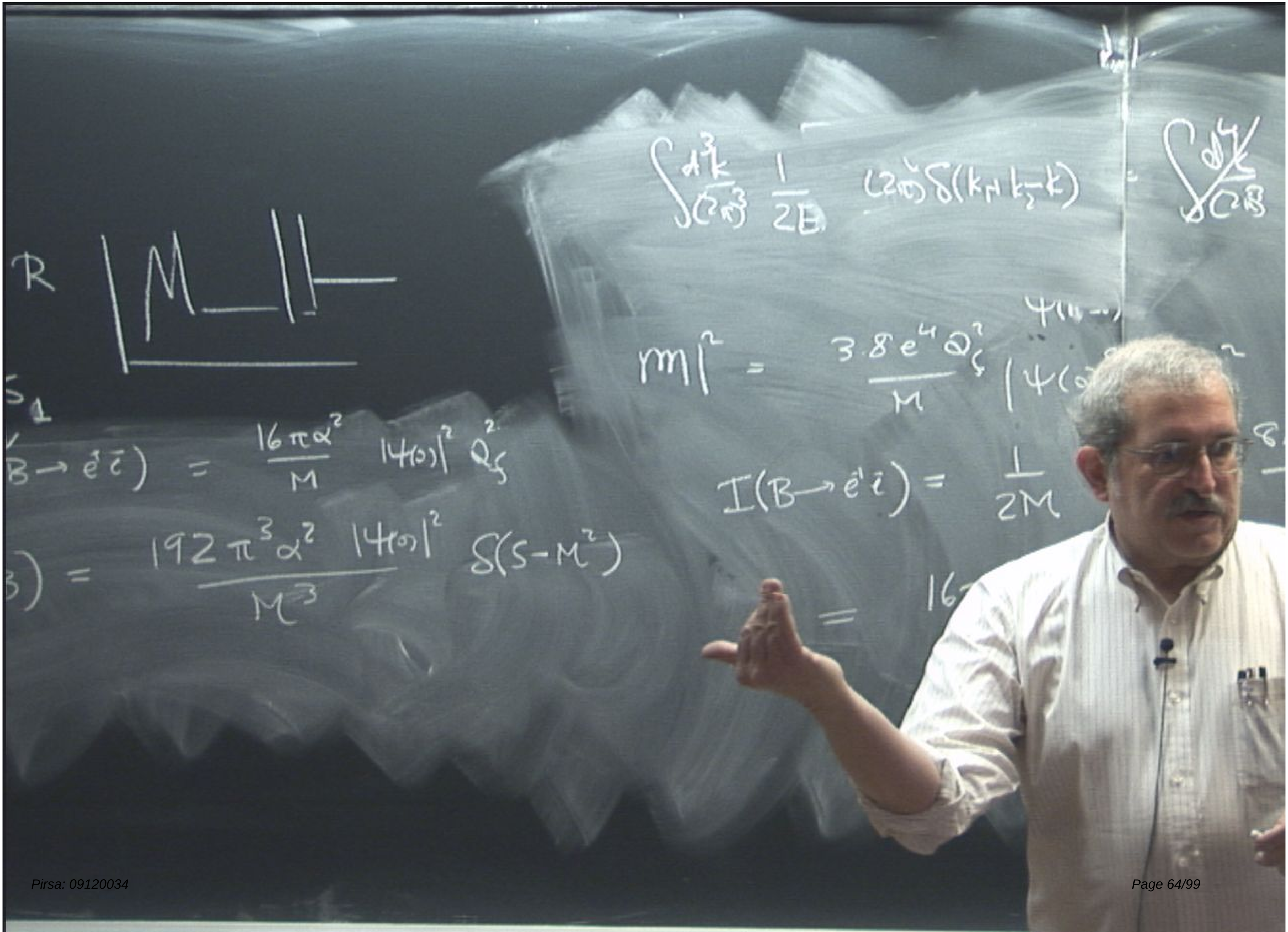
$$|m|^2 = \frac{3 \cdot 8 e^4 Q_f^2}{M} |\psi(0)|^2 |\vec{n} \cdot \vec{\varepsilon}|^2$$

$$\Gamma(B \to e^+ e^-) = \frac{1}{2M} \frac{1}{8\pi} \frac{8 \cdot 3}{M} Q_f^2 |\psi(0)|^2$$

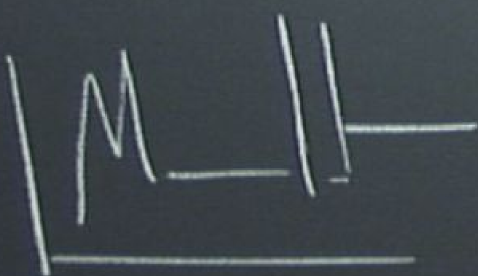
$$= \frac{16\pi\alpha^2}{M^2} |\psi(0)|^2 Q_f^2$$

$$\sum = \frac{1}{\sqrt{2}} \left(\frac{\vec{n} \cdot \vec{\sigma}}{\sqrt{2}}\right)$$

spin


$\int \frac{d^3k}{(2\pi)^3} \frac{1}{2E} (2\pi)^4 \delta(k_1 + k_2 - k)$
$\int \frac{d^4k}{(2\pi)^4}$
R
$|\mathcal{M}|^2 = \frac{3 \cdot 8 e^4 Q_q^2}{M} |\psi(0)|^2$
$\Gamma(B \to e^+ e^-) = \frac{16\pi\alpha^2}{M} |\psi(0)|^2 Q_q^2$
$\Gamma(B \to e^+ e^-) = \frac{1}{2M}$
$) = \frac{192\pi^3\alpha^2 |\psi(0)|^2}{M^3} \delta(s - M^2)$

$$\int \frac{d^3k}{(2\pi)^3}\,\frac{1}{2E}\,(2\pi)^4\,\delta(k_1+k_2-k) = \int \frac{d^4k}{(2\pi)^3}$$

R 

$\psi(\ldots)$

$$|\mathcal{M}|^2 = \frac{3\cdot 8\,e^4 Q_q^2}{M}\,|\psi(0)|^2\,|\vec{\pi}\cdot\vec{\epsilon}\,|^2$$

S_1

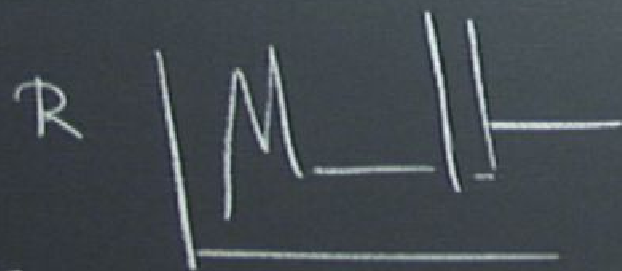
$$\Gamma(B\to e^+e^-) = \frac{16\pi\alpha^2}{M}\,|\psi(0)|^2\,Q_q^2$$

$$\Gamma(B\to e^+e^-) = \frac{1}{2M}\,\frac{1}{8\pi}$$

$$\sigma(\ldots B) = \frac{192\pi^3\alpha^2\,|\psi(0)|^2}{M^3}\,\delta(s-M^2)$$

$$= \frac{16\pi\alpha^2}{M^2}\,|\psi(0)|^2\,Q$$

Σ



n^3S_1

$$\Gamma(B \to e^+e^-) = \frac{16\pi\alpha^2}{M}|\psi(0)|^2 Q_q^2$$

$$\sigma(e^+e^- \to B) = \frac{192\pi^3\alpha^2|\psi(0)|^2}{M^3}\,\delta(s-M^2)$$

$$\sigma(e^+e^- \to X) = 4\pi^2\frac{(2J+1)}{M}\,\Gamma(X \to e^+e^-)\,\delta(s-M^2)$$

$\psi(0)$

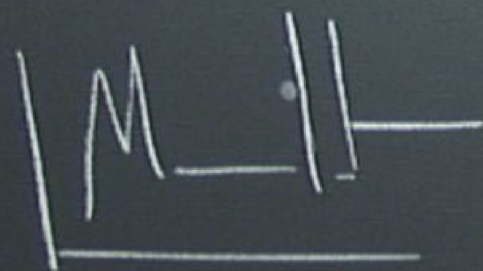
$\frac{4 Q_q^2}{M}|\psi(0)$

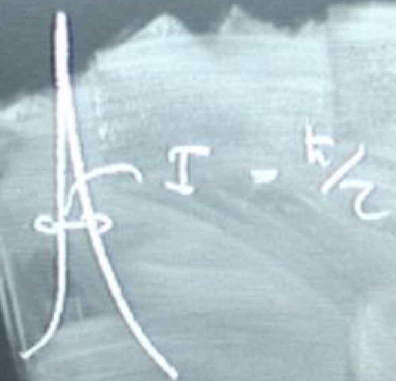
$\frac{1}{2M}$

$\pi\alpha^2$

Σ

R



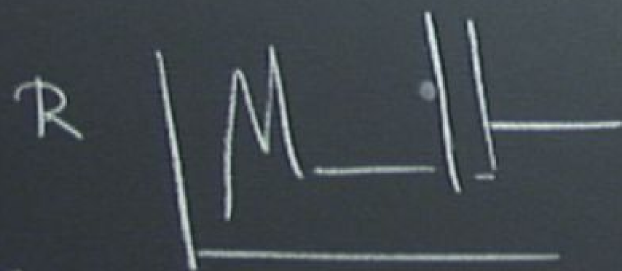


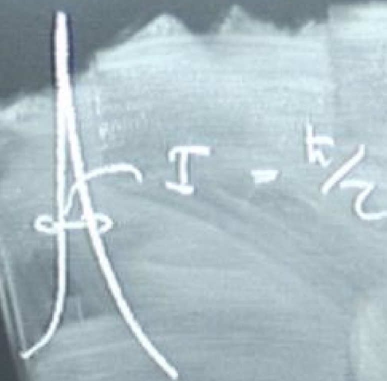
n^3S_1

$$\Gamma(B \to e^+e^-) = \frac{16\pi\alpha^2}{M} |\psi(0)|^2 Q_q^2$$

$$\sigma(e^+e^- \to B) = \frac{192\pi^3\alpha^2 |\psi(0)|^2}{M^3} \delta(s-M^2)$$

$$\sigma(e^+e^- \to X) = 4\pi^2 \frac{(2J+1)\, \Gamma(X \to e^+e^-)}{M} \delta(s-M^2)$$



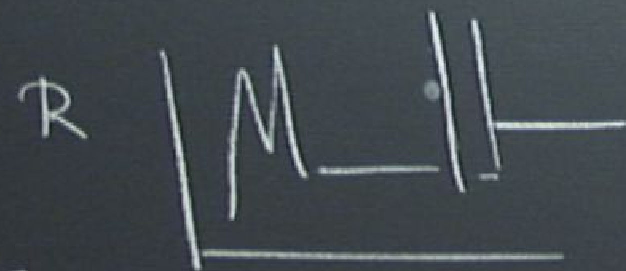


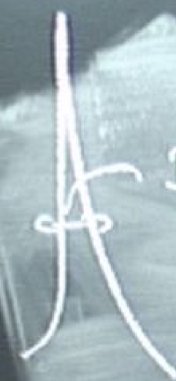
n^3S_1

$$\Gamma(B\to e^+e^-) = \frac{16\pi\alpha^2}{M}|\psi(0)|^2 Q_q^2$$

$$\sigma(e^+e^-\to B) = \frac{192\pi^3\alpha^2\,|\psi(0)|^2}{M^3}\,\delta(s-M^2)$$

$$\sigma(e^+e^-\to X) = 4\pi^2\,\frac{(2J+1)\,\Gamma(X\to e^+e^-)}{M}\,\delta(s-M^2)$$





$\Gamma \sim \hbar/2$

$n\,^3S_1$

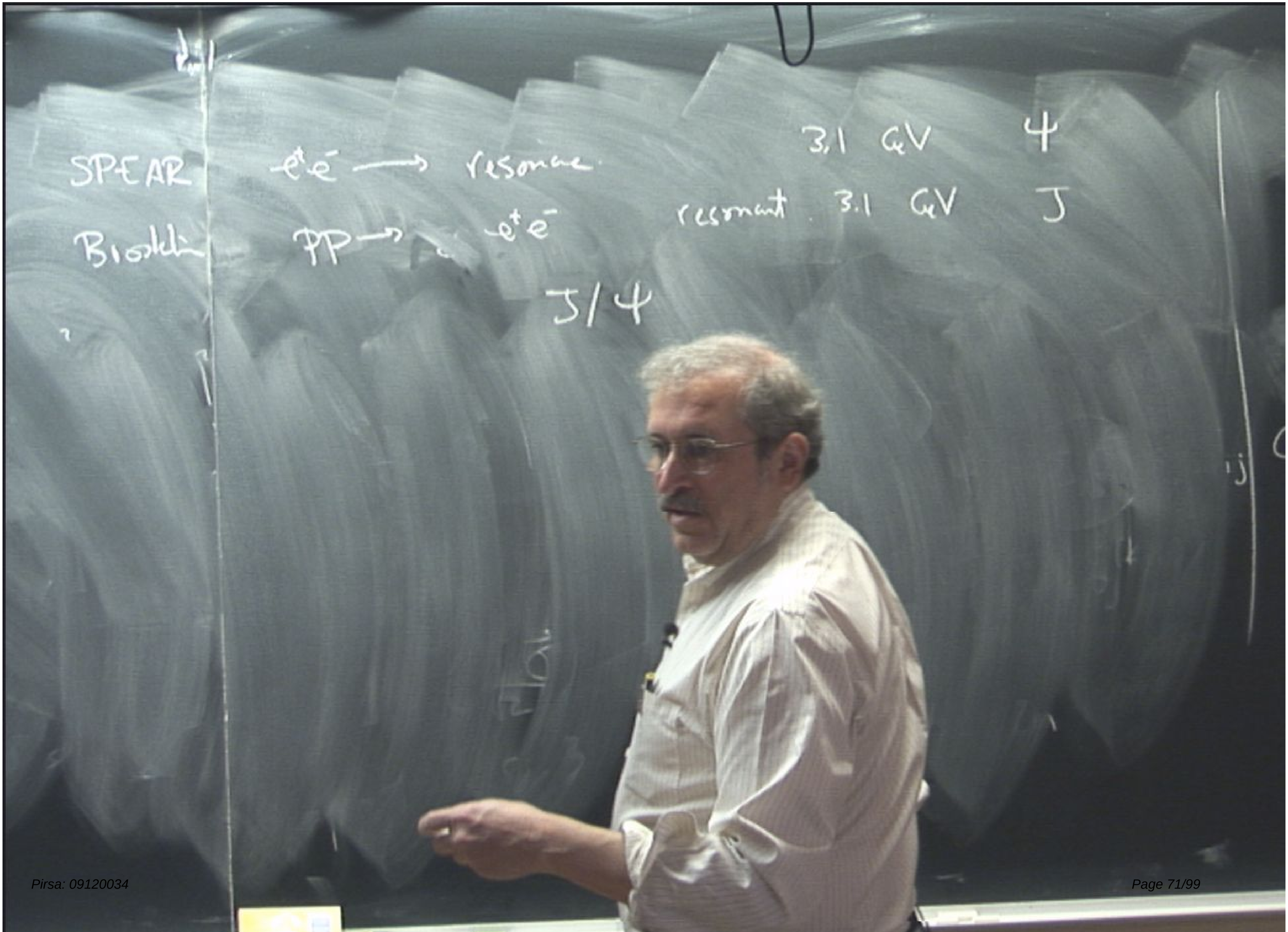
$$\Gamma(B \to e^+e^-) = \frac{16\pi\alpha^2}{M}|\psi(0)|^2 Q_q^2$$

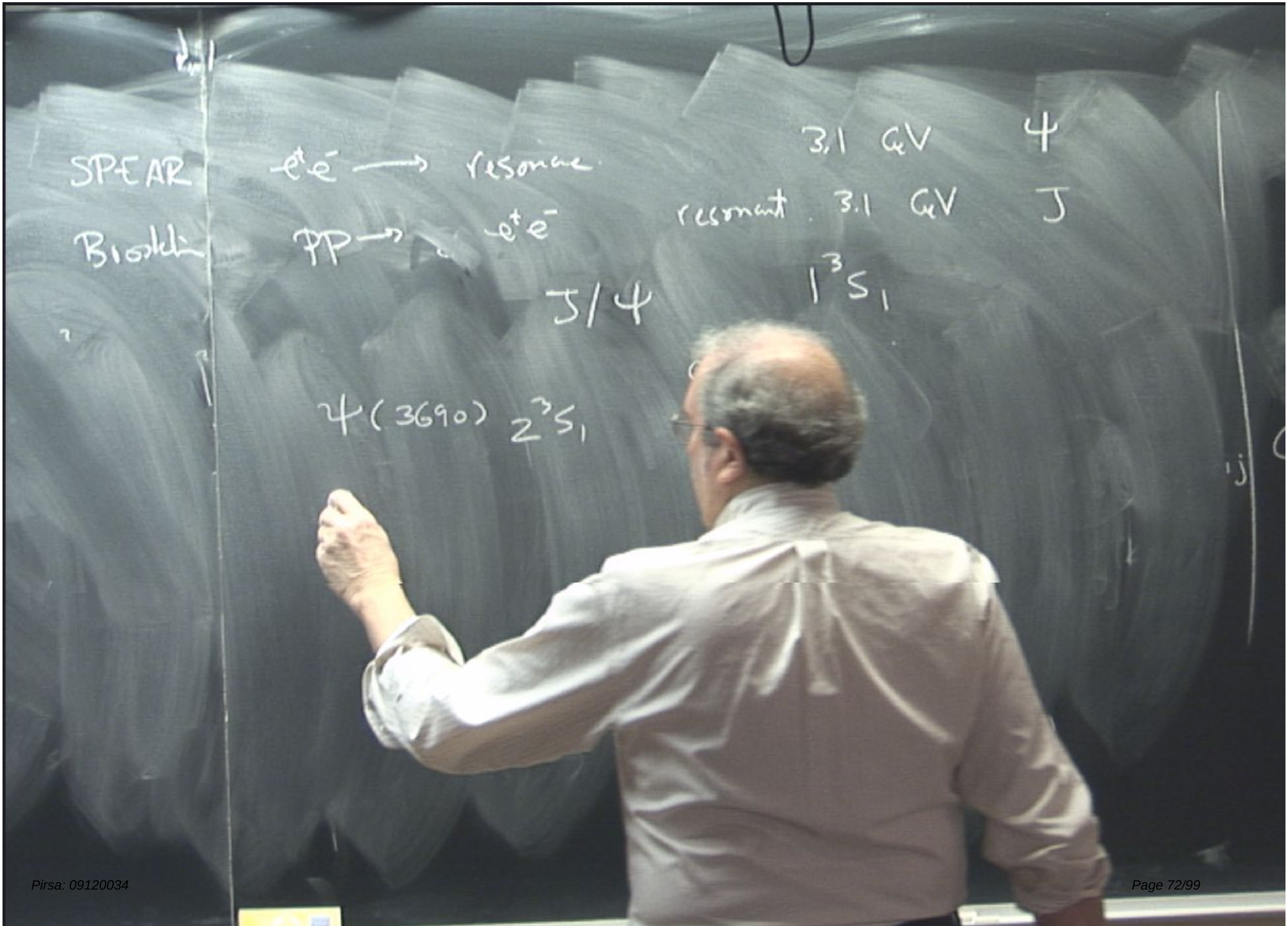
$$\sigma(e^+e^- \to B) = \frac{192\pi^3\alpha^2 |\psi(0)|^2}{M^3}\delta(s-M^2)$$

$$\sigma(e^+e^- \to X) = 4\pi^2 \frac{(2J+1)\,\Gamma(X \to e^+e^-)}{M}\delta(s-M^2)$$

SPEAR $e^+e^- \longrightarrow$ resonance 3.1 GeV

Brookhaven $pp \longrightarrow e^+e^-$ resonant 3.1 GeV


SPEAR
e+e- → resonance
3.1 GeV ψ
pp → e+e-
resonant 3.1 GeV J
J/ψ


SPEAR $e^+e^- \longrightarrow$ resonance
3.1 GeV ψ
resonant 3.1 GeV J
$pp \longrightarrow e^+e^-$
J/ψ
1^3S_1
$\psi(3690)$ 2^3S_1

SPEAR $e^+e^- \longrightarrow$ resonance 3.1 GeV ψ

Brookhaven $pp \longrightarrow e^+e^-$ resonant 3.1 GeV J

J/ψ 1^3S_1

$c\bar{c}$

$\psi(3690)$ 2^3S_1

$b\bar{b}$

SPEAR $e^+e^- \longrightarrow$ resonance 3.1 GeV ψ

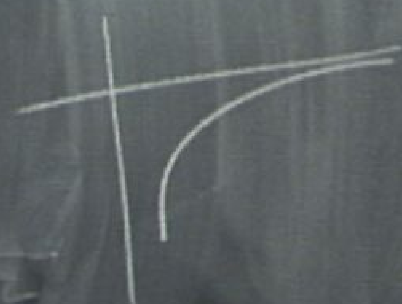
Brookhaven $pp \to e^+e^-$ resonant 3.1 GeV J

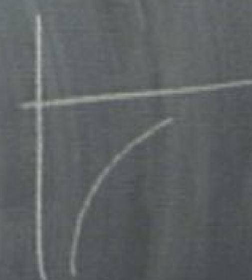
J/ψ 1^3S_1

$c\bar{c}$

$\psi(3690)$ 2^3S_1

$b\bar{b}$





AR $e^+e^- \longrightarrow$ resonance

$p\bar{p} \longrightarrow e^+e^-$

J/ψ

$\psi(3690)\ 2^3S_1$

$b\bar{b}$

3.7 2S $C=-1$ γ

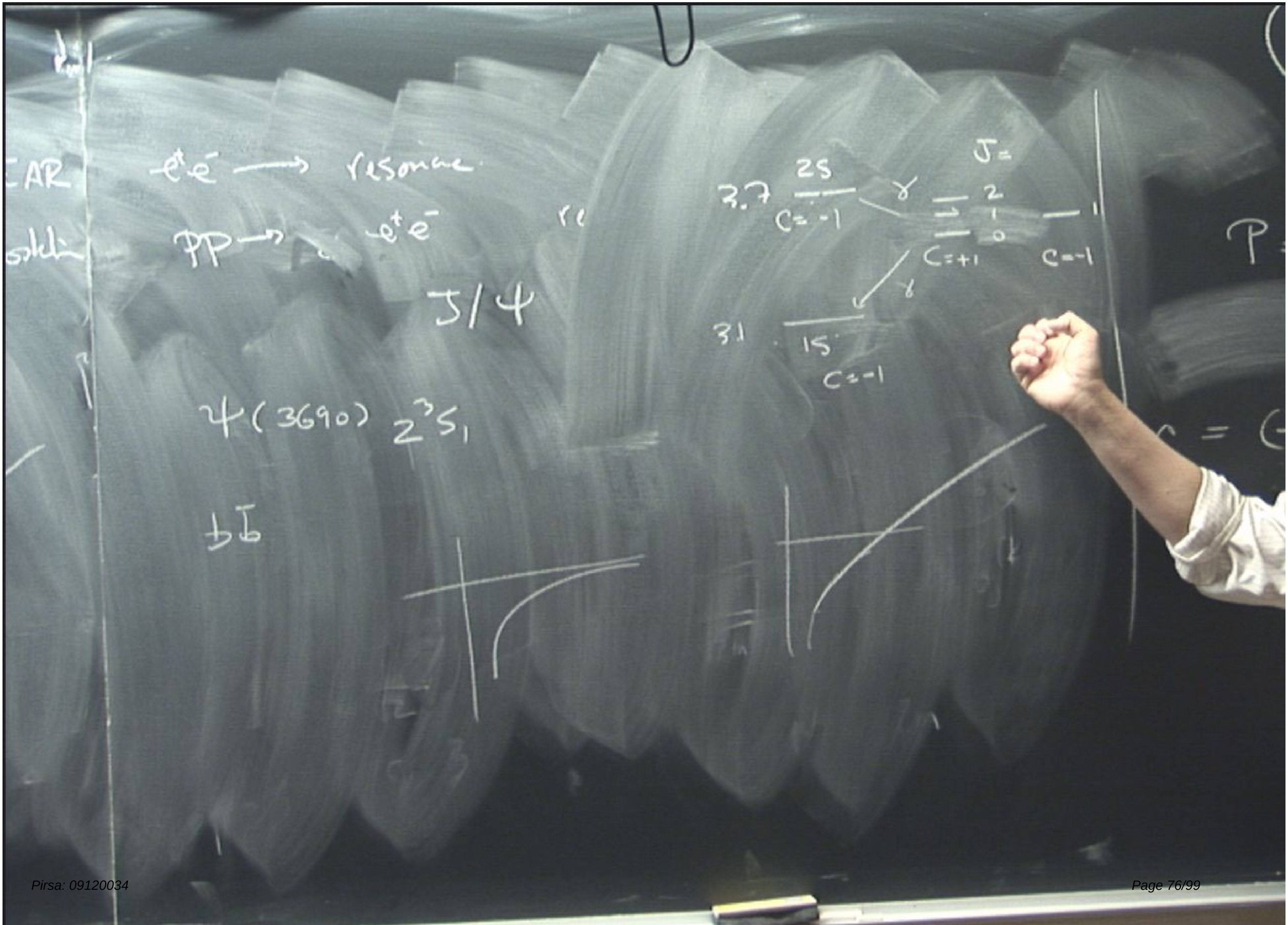
1P $C=+1$

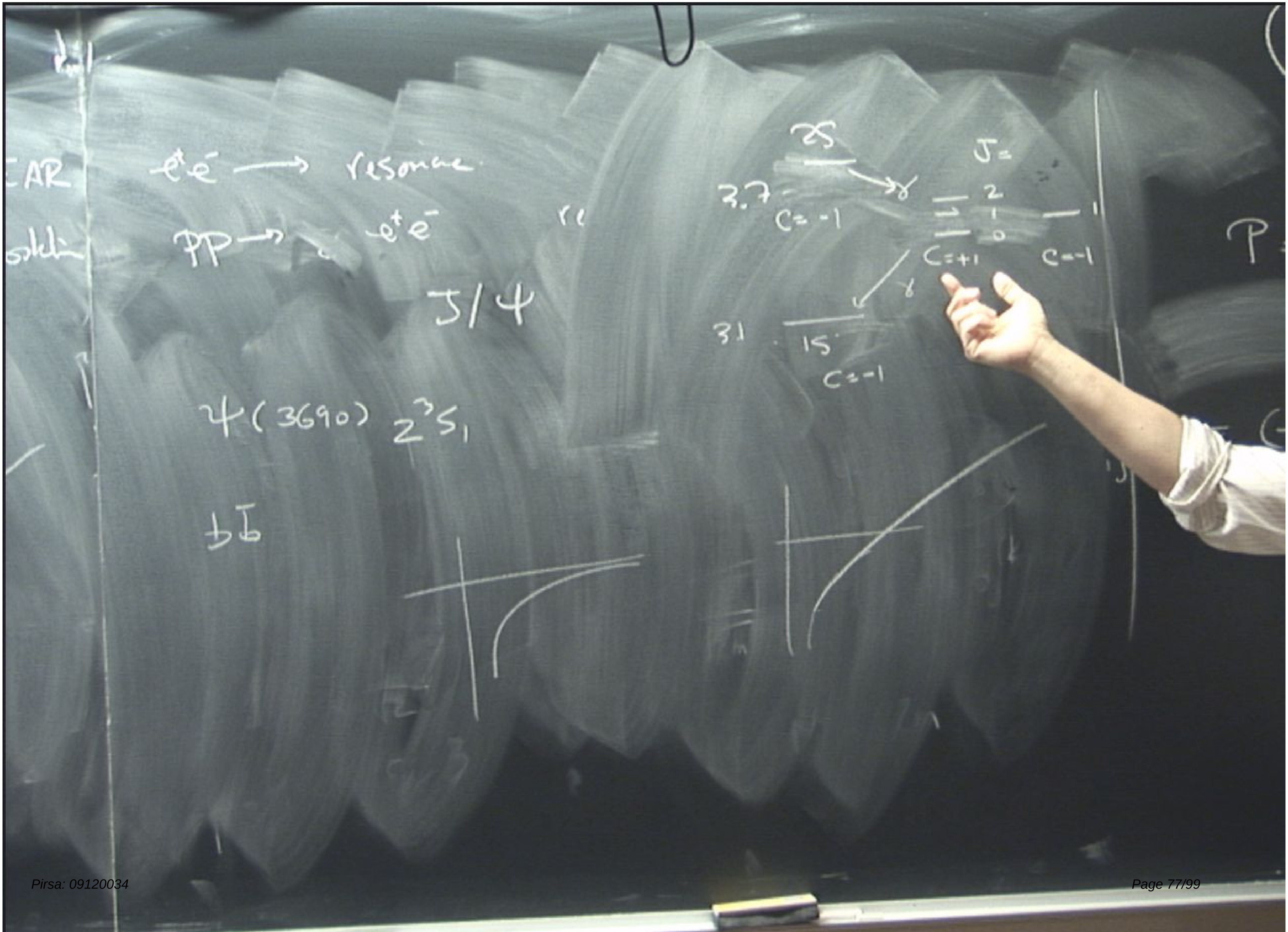
γ

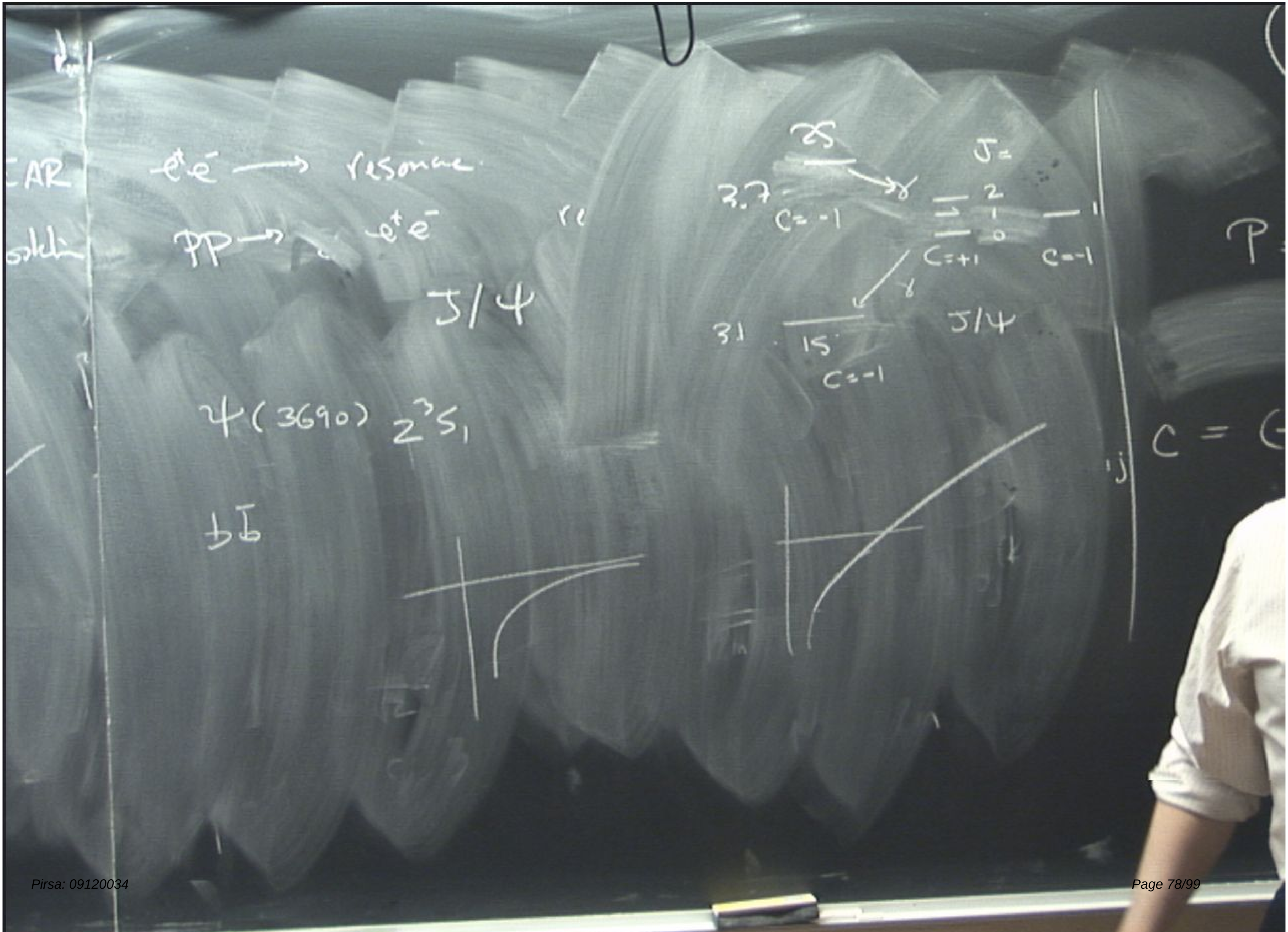
3.1 1S $C=-1$

$P=$

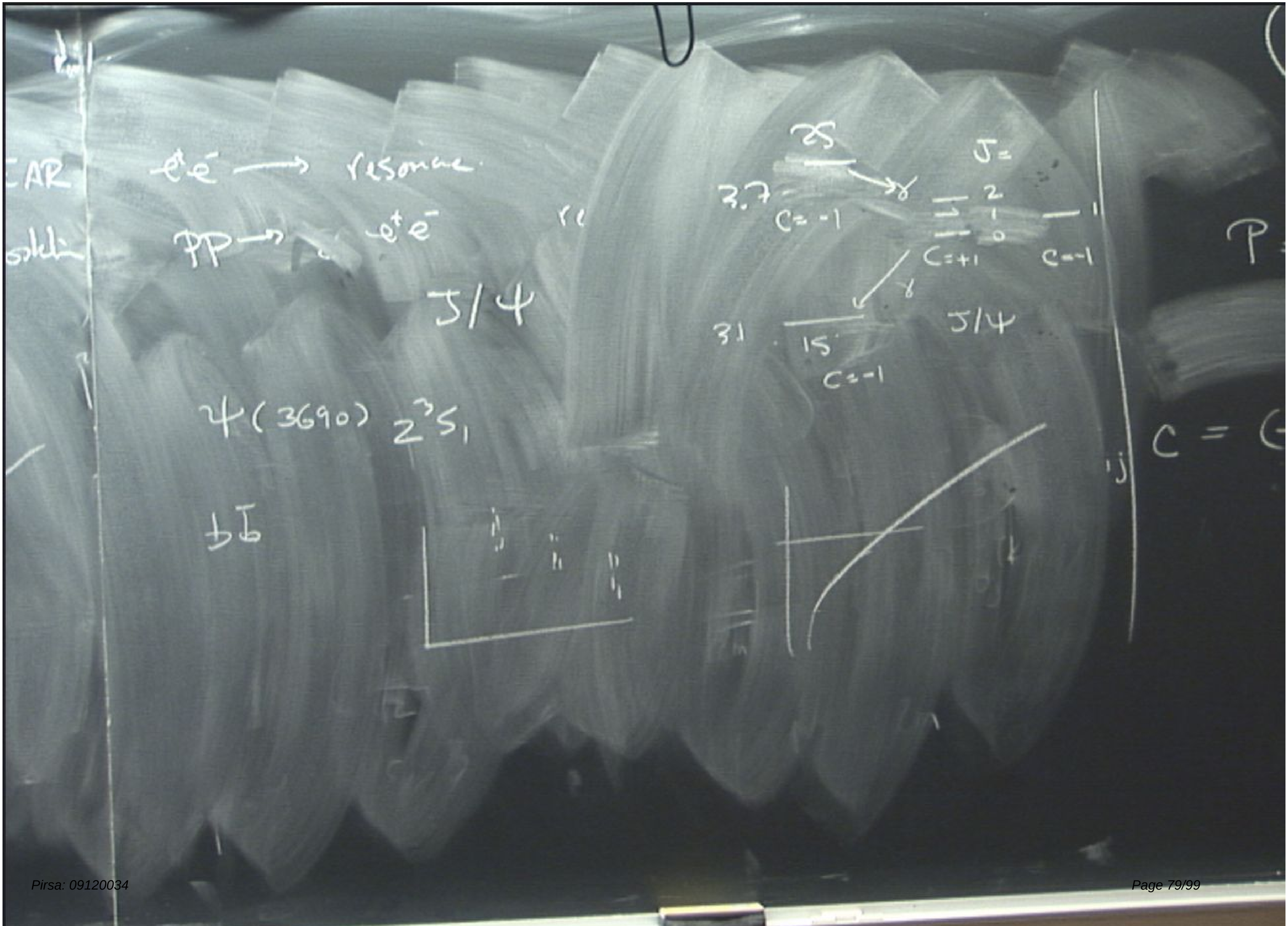
$C=$

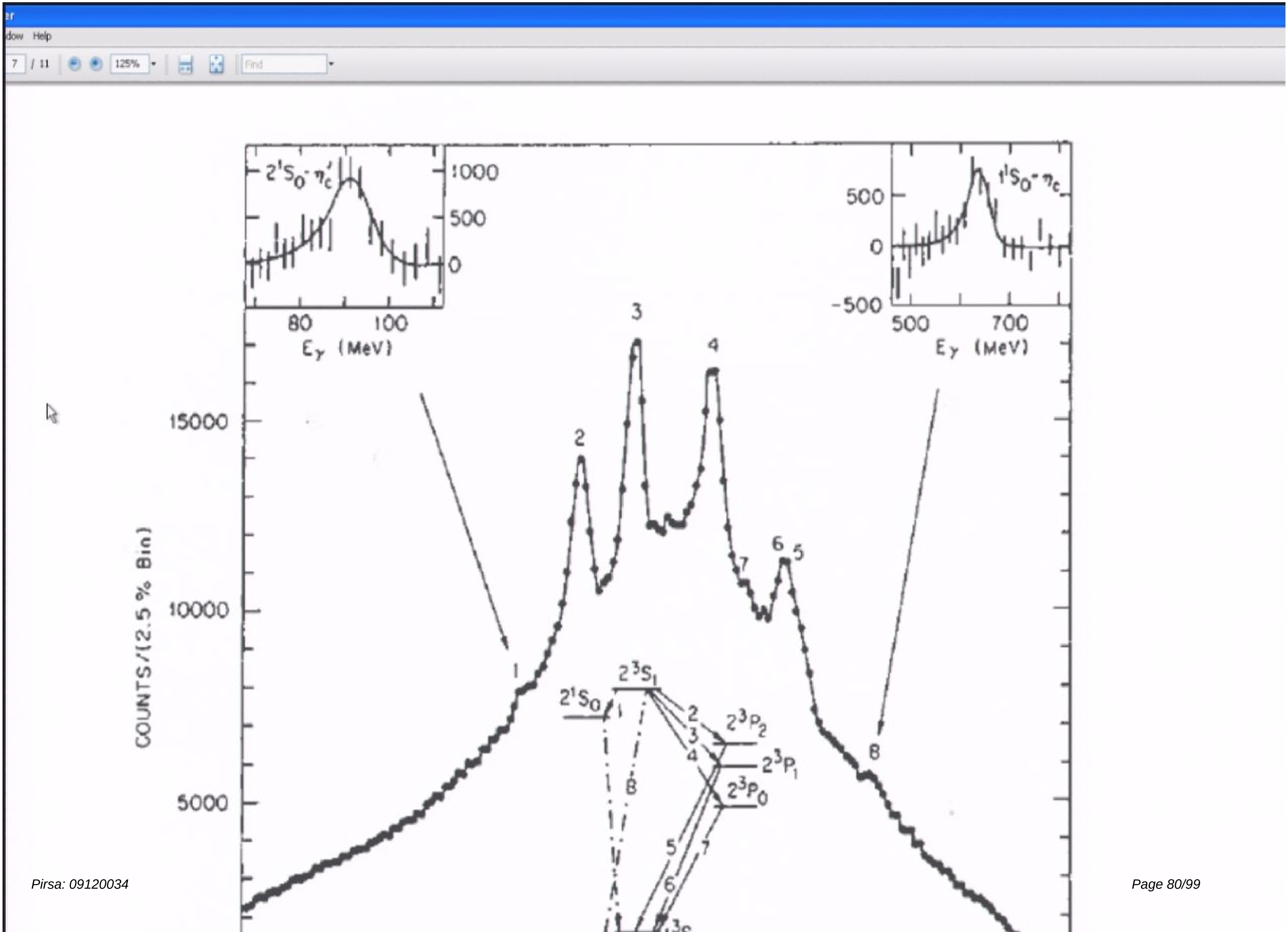

e+e- → resonance
pp → e+e-
J/ψ
ψ(3690) 2³S₁
b b̄
3.7 2S
C=-1
J=
2
1
0
C=+1
C=-1
3.1 1S
C=-1
γ
γ


AR
e⁺e⁻ ⟶ resonance
PP ⟶ e⁺e⁻
J/ψ
ψ(3690) 2³S₁
bb̄
2S
3.7
C = -1
J =
2
1
0
1
C=+1
C=-1
31
1S
C=-1
P



EAR
e+e- → resonance
PP → e+e-
J/ψ
ψ(3690) 2³S₁
b b̄
3.7
C=-1
J=
2
1
0
C=+1
C=-1
3.1
1S
C=-1
J/ψ
P
C =


$e^+e^- \longrightarrow$ resonance
$p\bar{p} \longrightarrow e^+e^-$
J/ψ
$\psi(3690)$ 2^3S_1
$b\bar{b}$
3.7
C = -1
J =
2
1
0
C = +1
C = -1
3.1
1S
C = -1
J/ψ
P =
C =



$2^1S_0 - \eta_c'$
1000
500
0
80
100
E_γ (MeV)
$1^1S_0 - \eta_c$
500
0
-500
500
700
E_γ (MeV)
15000
10000
5000
COUNTS/(2.5 % Bin)
1
2
3
4
5
6
7
8
2^3S_1
2^1S_0
2^3P_2
2^3P_1
2^3P_0

AR $e^+e^- \longrightarrow$ resonance

$p\bar{p} \longrightarrow e^+e^-$

J/ψ

$\psi(3690)$ 2^3S_1

$b\bar{b}$

η_c' 2^1S_0 $C=-1$

$2S$ γ

$J=$ 2 1 0 1

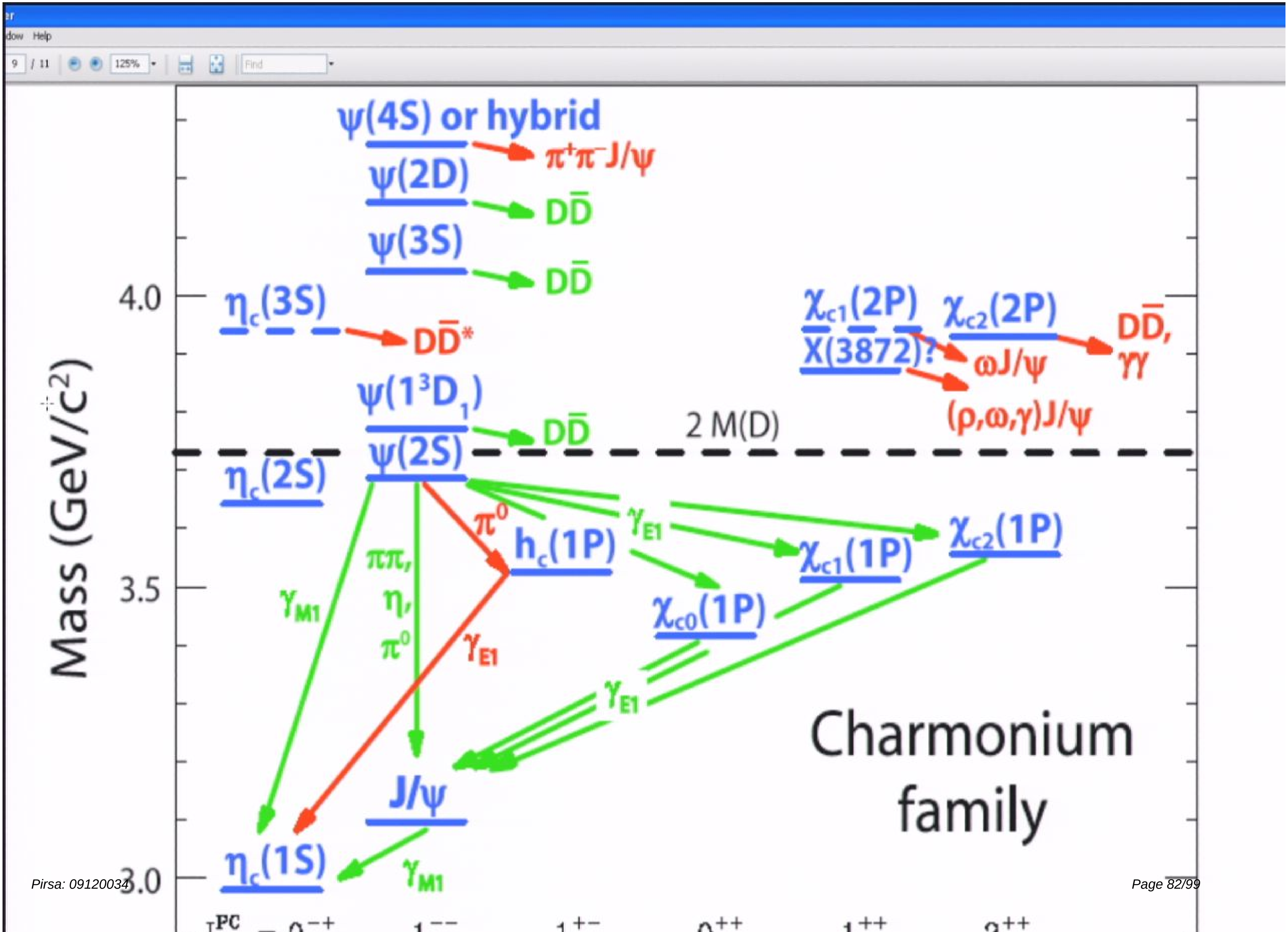
$C=+1$ $C=-1$

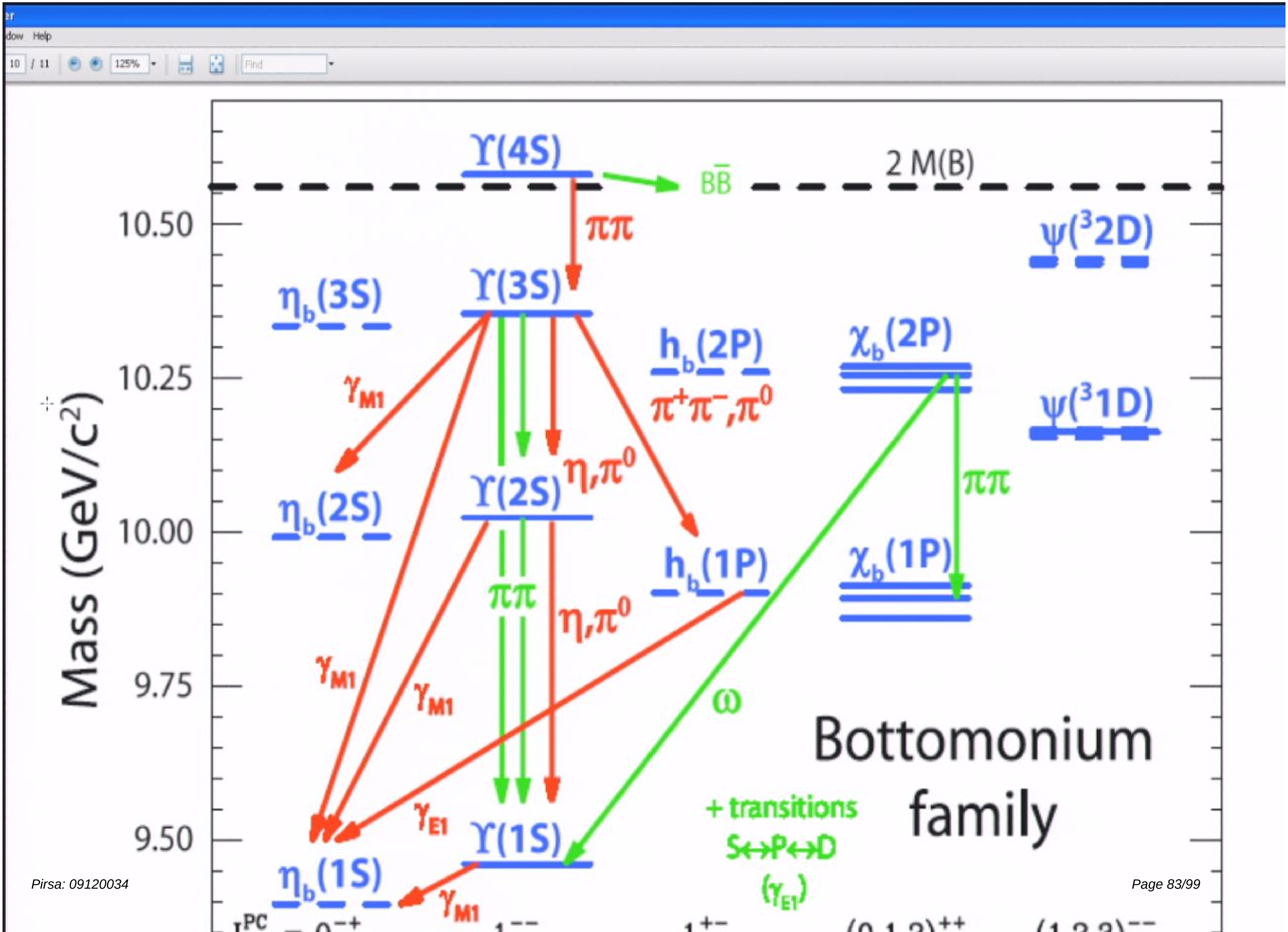
η_c 1^1S_0 3γ $1S$ $C=-1$

J/ψ

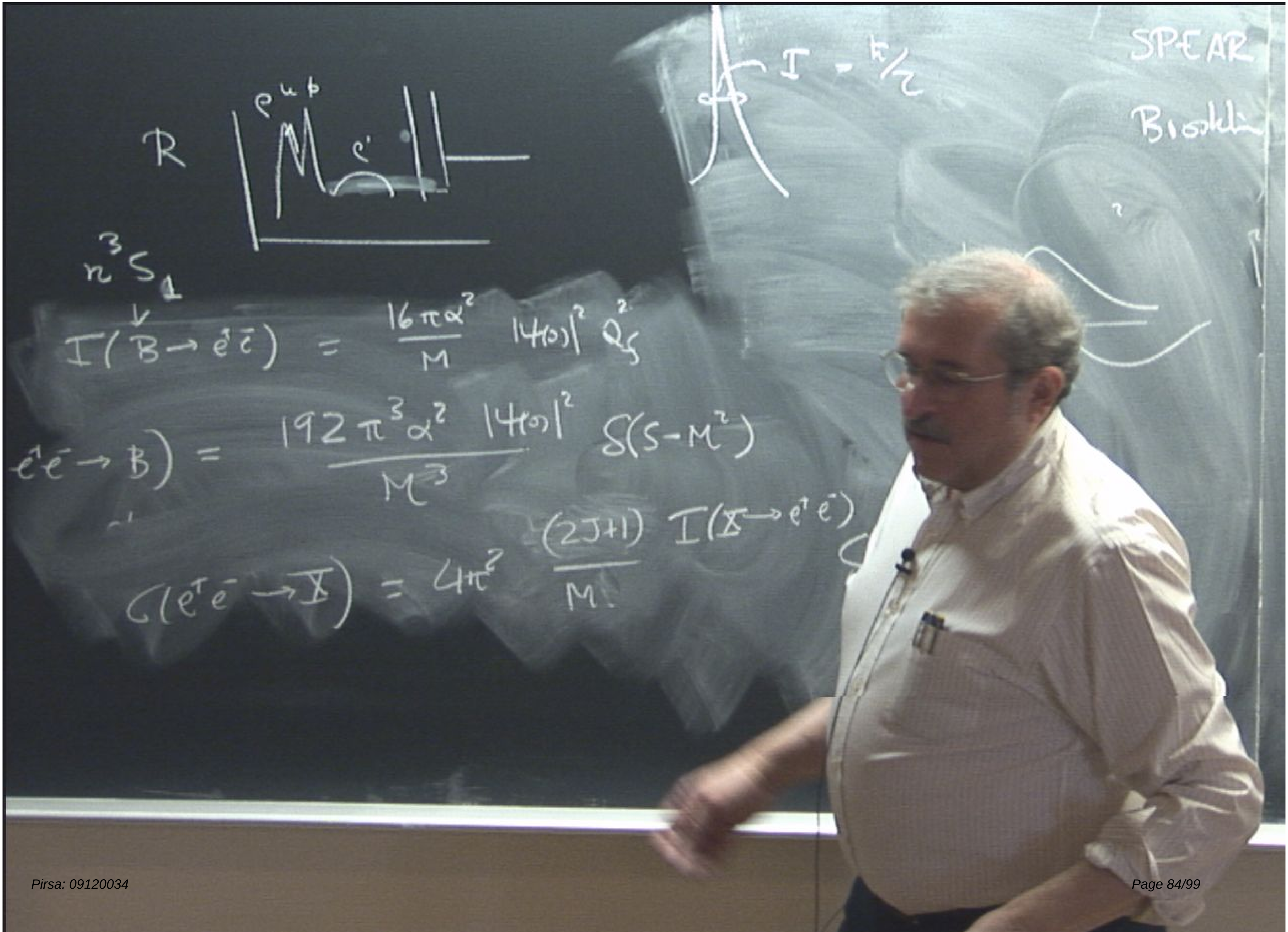
$P=$

$C=$

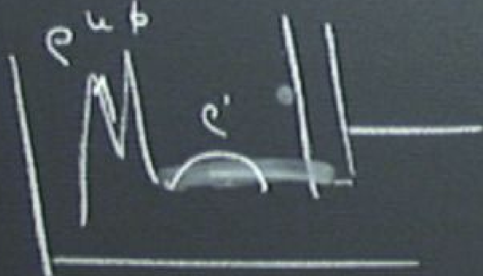

dow Help
9 / 11
125%
Find
ψ(4S) or hybrid
π⁺π⁻J/ψ
ψ(2D)
DD̄
ψ(3S)
DD̄
4.0
η_c(3S)
DD̄*
χ_c1(2P)
χ_c2(2P)
X(3872)?
DD̄,
γγ
ωJ/ψ
(ρ,ω,γ)J/ψ
Mass (GeV/c²)
ψ(1³D₁)
DD̄
2 M(D)
ψ(2S)
η_c(2S)
π⁰
γ_E1
h_c(1P)
χ_c2(1P)
χ_c1(1P)
3.5
γ_M1
ππ,
η,
π⁰
γ_E1
χ_c0(1P)
γ_E1
Charmonium
family
J/ψ
η_c(1S)
γ_M1
3.0
J^PC = 0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺

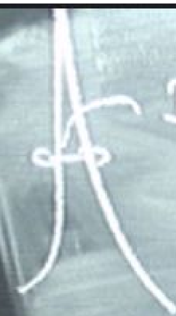


Mass (GeV/c²)
10.50
10.25
10.00
9.75
9.50
Υ(4S)
BB̄
2 M(B)
ππ
ψ(³2D)
η_b(3S)
Υ(3S)
h_b(2P)
χ_b(2P)
γ_M1
π⁺π⁻,π⁰
ψ(³1D)
η,π⁰
η_b(2S)
Υ(2S)
ππ
h_b(1P)
χ_b(1P)
ππ
η,π⁰
γ_M1
γ_M1
ω
Bottomonium
family
γ_E1
Υ(1S)
+ transitions
S↔P↔D
(γ_E1)
η_b(1S)
γ_M1


SPEAR
R
n^3S_1
$\Gamma(B \to e^+e^-) = \frac{16\pi\alpha^2}{M}|\psi(0)|^2 Q_q^2$
$\sigma(e^+e^- \to B) = \frac{192\pi^3\alpha^2|\psi(0)|^2}{M^3}\delta(s-M^2)$
$\sigma(e^+e^- \to X) = 4\pi^2\frac{(2J+1)}{M}\Gamma(X \to e^+e^-)$

R





$\Gamma = k/2$

SPEAR

Brookh

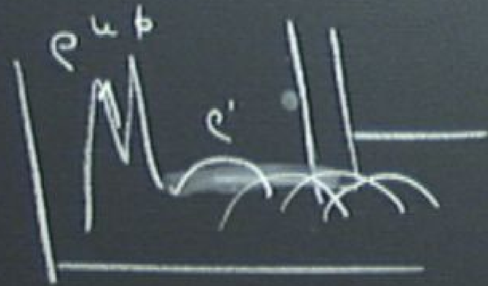
n^3S_1

$$\Gamma(B \to e^+e^-) = \frac{16\pi\alpha^2}{M} |\psi(0)|^2 Q_q^2$$

$$\sigma(e^+e^- \to B) = \frac{192\pi^3\alpha^2 |\psi(0)|^2}{M^3} \delta(s-M^2)$$

$$\sigma(e^+e^- \to X) = 4\pi^2 \frac{(2J+1)}{M} \Gamma(X \to e^+e^-) \delta(s-M^2)$$

R



$n\,{}^3S_1$

$\Gamma = \hbar/\tau$

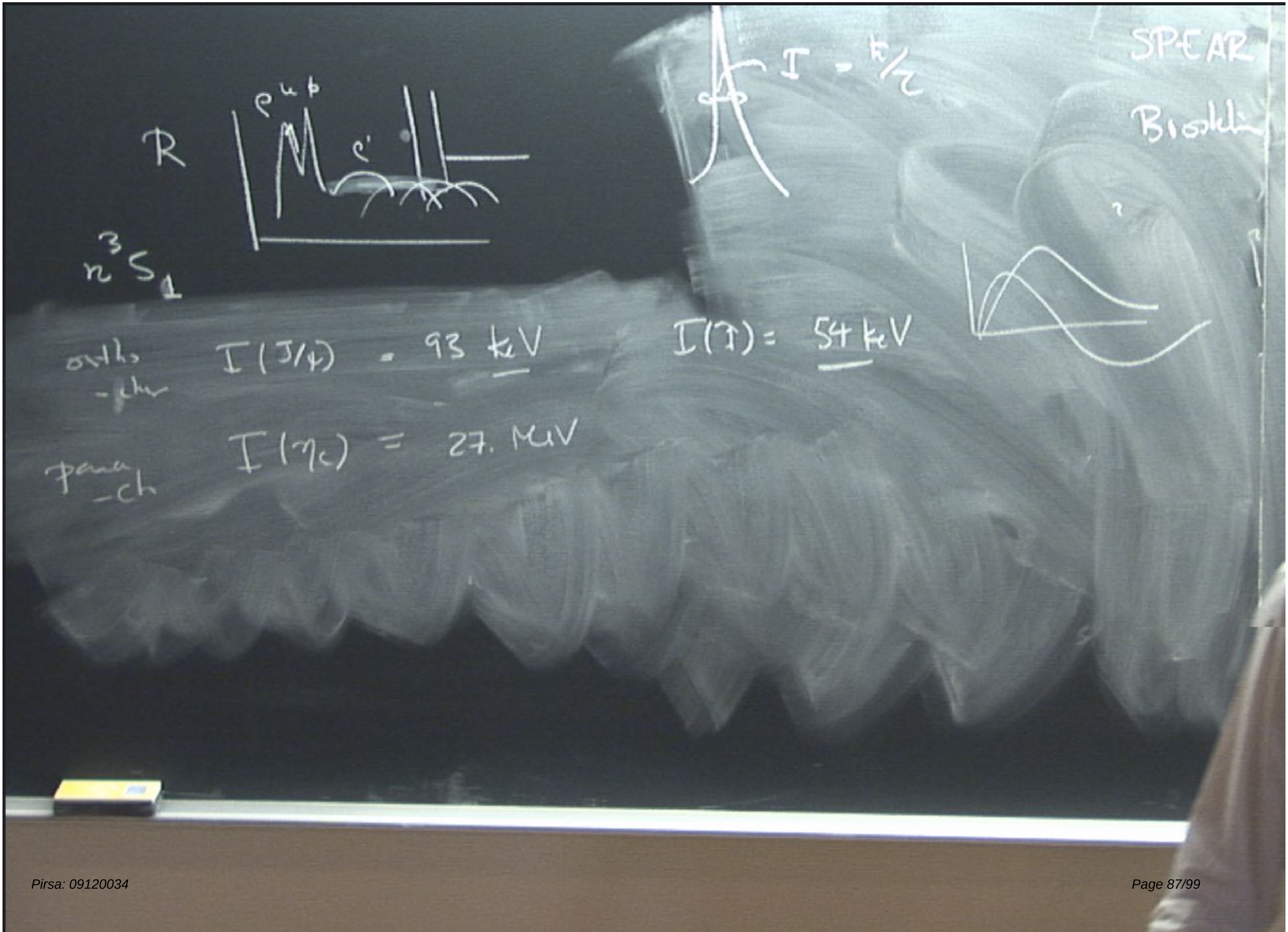
SPEAR

Brookh

$\Gamma(J/\psi) = 93$ keV

$\Gamma(\Upsilon) = 54$ keV

$\Gamma(\eta_c) = 27.$ MeV

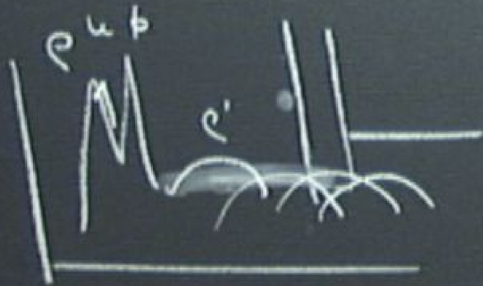

R
ρ ω φ
ψ'
n³S₁
Γ = ħ/τ
SPEAR
Γ(J/ψ) = 93 keV
Γ(η_c) = 27. MeV
Γ(Υ) = 54 keV
para
-ch

SPEAR

Brookh

$\Gamma = \hbar/\tau$

R

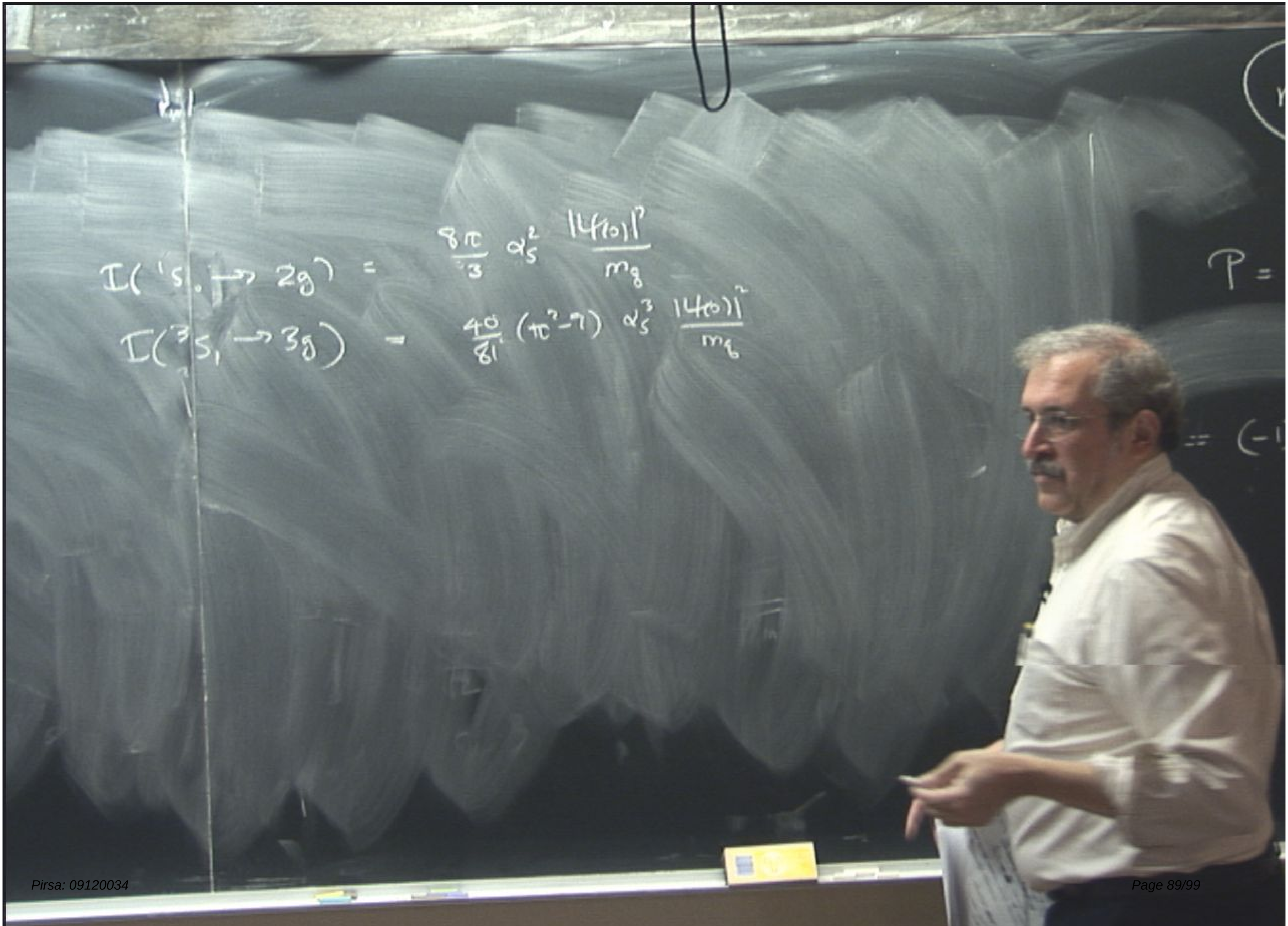


n^3S_1

ortho -char $\Gamma(J/\psi) = 93$ keV

$\Gamma(\Upsilon) = 54$ keV

para -ch $\Gamma(\eta_c) = 27.$ MeV


$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\alpha_s^2 \frac{|\psi(0)|^2}{m_q}$
$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}(\pi^2-9)\alpha_s^3 \frac{|\psi(0)|^2}{m_q}$

$$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\,\alpha_s^2\,\frac{|\psi(0)|^2}{m_q^2}$$

$$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}\,(\pi^2-9)\,\alpha_s^3\,\frac{|\psi(0)|^2}{m_q^2}$$

$P =$

$C =$

$$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\,\alpha_s^2\,\frac{|\psi(0)|^2}{m_q}$$

$$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}\,(\pi^2-9)\,\alpha_s^3\,\frac{|\psi(0)|^2}{m_q}$$

$P =$

$C = (-1$

$$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\,\alpha_s^2\,\frac{|\psi(0)|^2}{m_q}$$

$$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}(\pi^2-9)\,\alpha_s^3\,\frac{|\psi(0)|^2}{m_q}$$

$$\alpha_s \sim 0.1$$

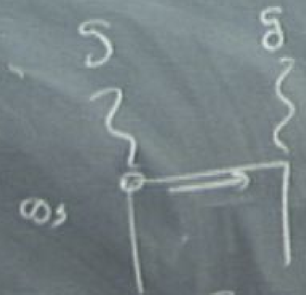
$P =$

$C =$

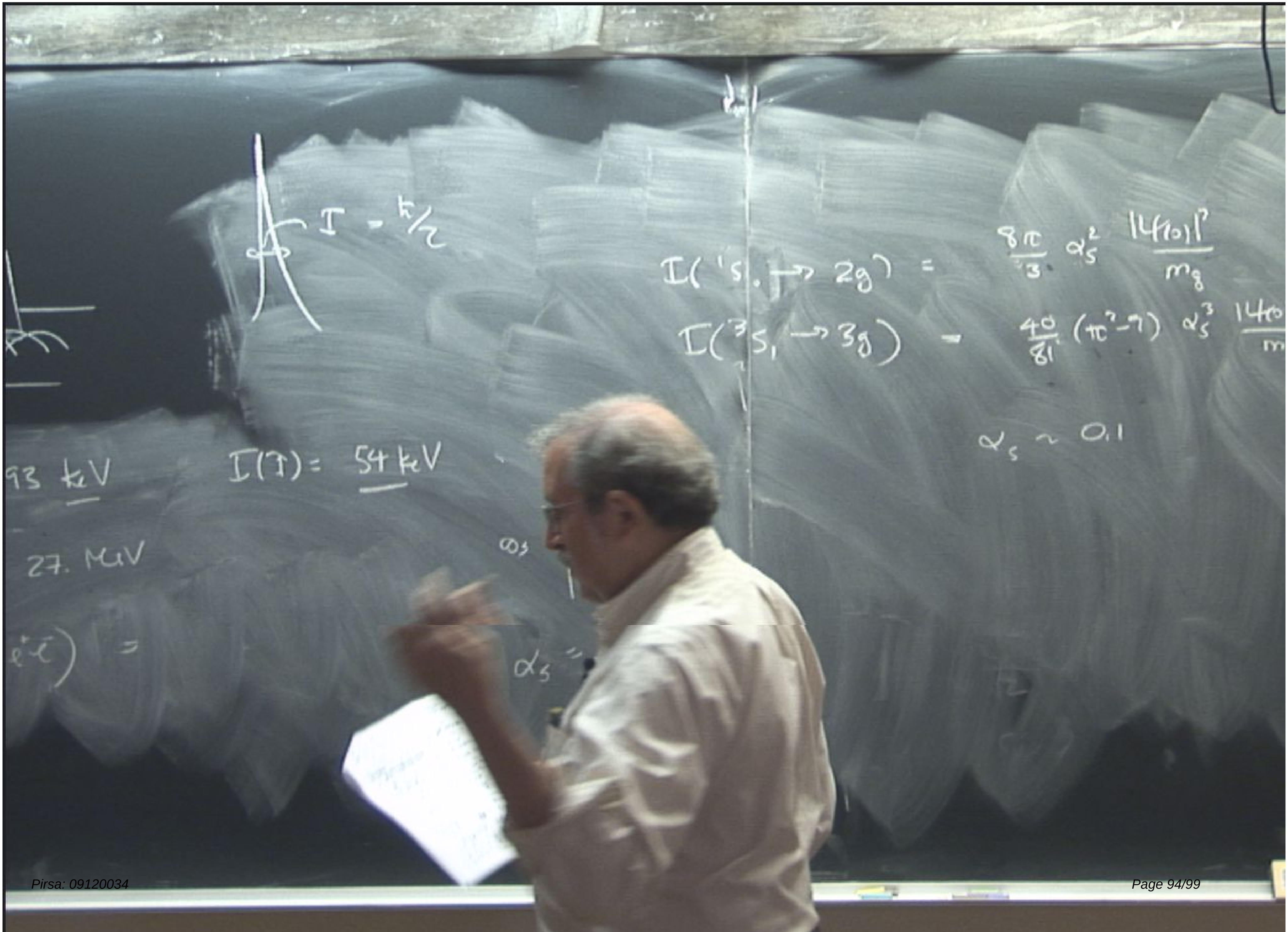
$$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\,\alpha_s^2\,\frac{|\psi(0)|^2}{m_q^2}$$

$$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}(\pi^2-9)\,\alpha_s^3\,\frac{|\psi(0)|^2}{m_q^2}$$

$$\alpha_s \sim 0.1$$



$$\alpha_s = \frac{g_s^2}{4\pi}$$



Γ = k/2
Γ(¹S₀ → 2g) = 8π/3 α_s² |ψ(0)|²/m_g
Γ(³S₁ → 3g) = 40/81 (π²−9) α_s³
α_s ~ 0.1
93 keV
Γ(Υ) = 54 keV
27. MeV

$\Gamma \sim \hbar/2$

$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\alpha_s^2 \frac{|\psi(0)|^2}{m_q}$

$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}(\pi^2-9)\,\alpha_s^3 \frac{|\psi(0)|^2}{m}$

93 keV

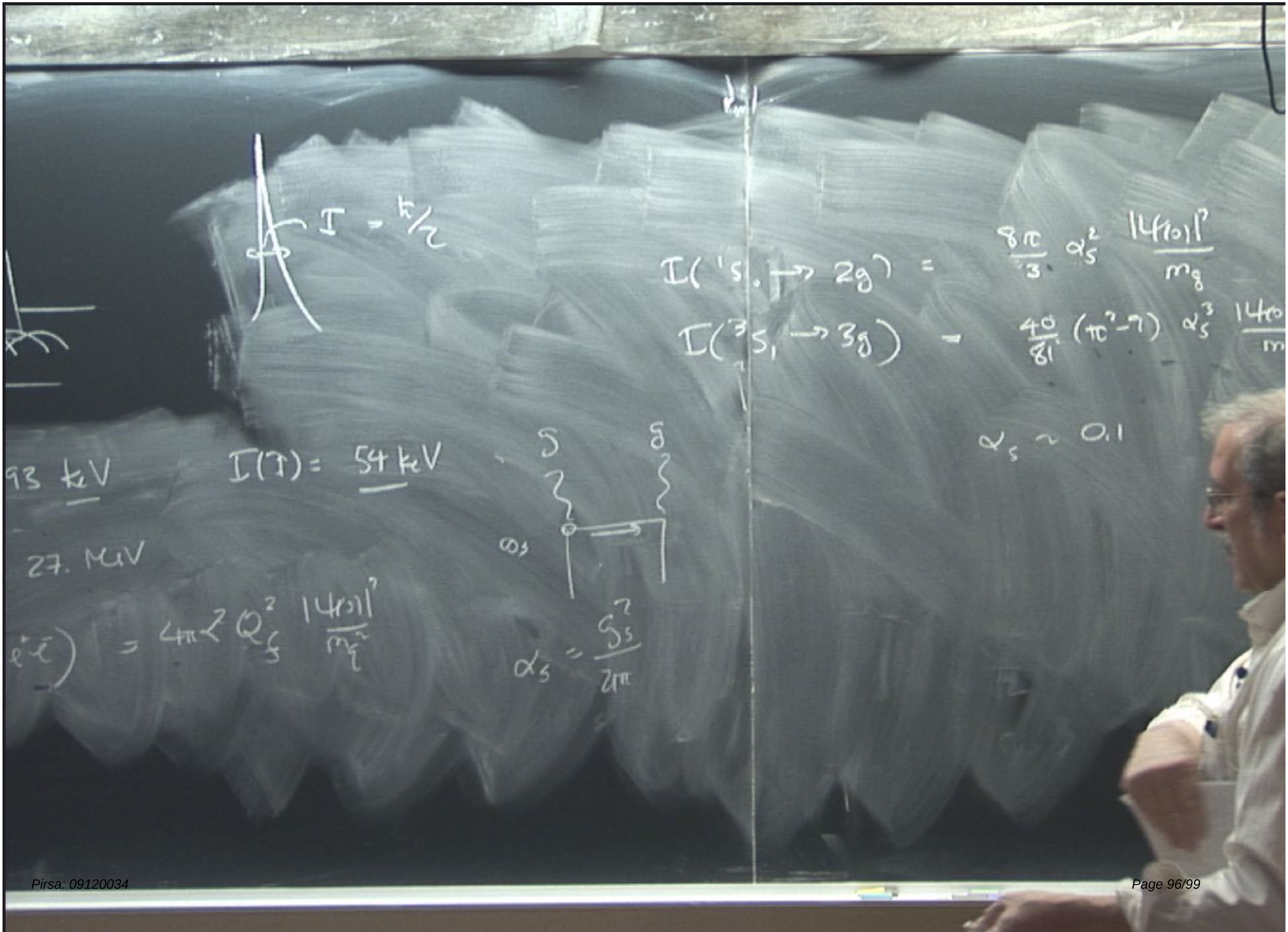
$\Gamma(\Upsilon) = 54$ keV

27. MeV

$\alpha_s \sim 0.1$

$(e^+e^-) = 4\pi\alpha^2 Q_f^2 \frac{|\psi(0)|^2}{m_q^2}$

$\alpha_s = \frac{g_s^2}{4\pi}$


Γ = ħ/τ
Γ(¹S₀ → 2g) = 8π/3 αs² |ψ(0)|²/mq
Γ(³S₁ → 3g) = 40/81 (π²−9) αs³
αs ~ 0.1
93 keV
Γ(Υ) = 54 keV
27. MeV
= 4πα² Qf² |ψ(0)|²/mf²
αs = gs²/2π

$\Gamma = \hbar/2$

$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3} \alpha_s^2 \frac{|\psi(0)|^2}{m_q}$

$\Gamma({}^3S_1 \to 3g) = \frac{40}{81} (\pi^2 - 9) \alpha_s^3 \frac{|\psi(0)|^2}{m}$

$\alpha_s \sim 0.1$

93 keV

$\Gamma(\Upsilon) = 54$ keV

27. MeV

$(e^+e^-) = 4\pi\alpha^2 Q_f^2 \frac{|\psi(0)|^2}{m_q^2}$

$= 5.6$ keV

$\alpha_s = \frac{g_s^2}{2\pi}$

$I = {}^{k}/_{2}$

$$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\alpha_s^2 \frac{|\psi(0)|^2}{m_g}$$

$$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}(\pi^2-9)\alpha_s^3 \frac{|\psi(0)|^2}{m_g}$$

$\alpha_s \sim 0.1$

$\Gamma) = \underline{54\,keV}$

g g

ω_3

$|\psi(0)|^2$ / m_g^2

$\alpha_s = \frac{g_s^2}{2\pi}$

$$\frac{\Gamma(\psi \to 3g)}{\Gamma(\psi \to e^+e^-)} = \frac{5}{18}\,\frac{\pi^2-9}{\pi}\,\frac{\alpha_s^3}{\alpha^2}$$

eV

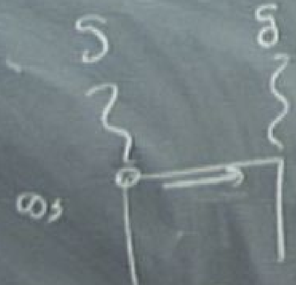
$= \pi/2$

$$\Gamma({}^1S_0 \to 2g) = \frac{8\pi}{3}\,\alpha_s^2\,\frac{|\psi(0)|^2}{m_q^2}$$

$$\Gamma({}^3S_1 \to 3g) = \frac{40}{81}(\pi^2-9)\,\alpha_s^3\,\frac{|\psi(0)|^2}{m_b^2}$$

$\alpha_s \sim 0.1$

54 keV



$$\alpha_s = \frac{g_s^2}{4\pi}$$

$$\frac{\Gamma(J/\psi \to 3g)}{\Gamma(J/\psi \to e^+e^-)} = \frac{5}{18}\,\frac{\pi^2-9}{\pi}\,\frac{\alpha_s^3}{\alpha^2}$$

$\alpha_s \sim 0.2$