Magnetic Field Quenching of Quarkonium Decay

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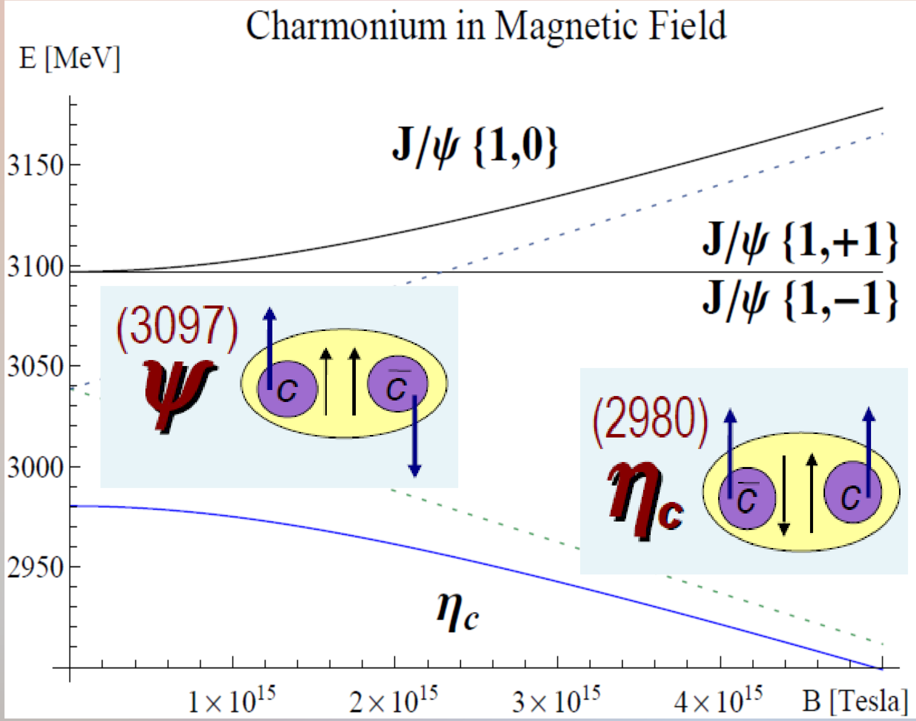
- ***n, p, Δ, Ξ, Σ, Λ, Ω*** **:** mag. moment
  $\mu_u, \mu_d, \mu_s \rightarrow \mu_c = 2\mu_s/3 \quad \mu_b = \mu_s/9$
- **Vector-meson** elmag. properties
  open-flavor: *D*,B*,K**
  quarkonium J/Ψ(cc'), ϒ(bb'), φ(ss')
- **J/Ψ and ϒ$_{(bb')}$ in magn. Field:**
  → **Mixing of η states with Ψ ,ϒ**
  → **Quenching (of Ψ,ϒ decays)**
- φ & **Conclusions**



(e⁺e⁻) = ortho-Ps ↔ J/Ψ = (cc')

PHYSICAL REVIEW VOLUME 98, NUMBER 6 JUNE 15, 1955

Static Magnetic Field Quenching of the Orthopositronium Decay

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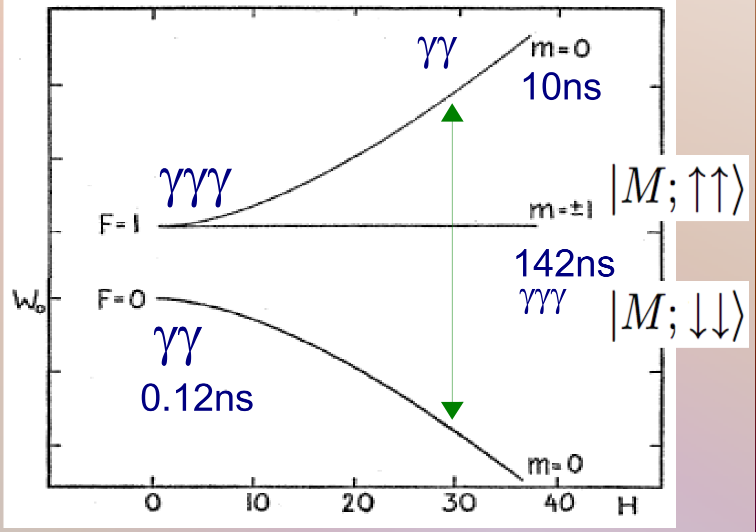
MAIN IDEA: ortho-Ps (e^+e^-) –> $J/\Psi = (cc')$

On the other hand, the $M=0$ state of orthopositronium has a small admixture of para-state due to the interaction with the magnetic field, and hence can decay either by three-quantum annihilation or by two-quantum annihilation. The relative probabilities of



- Quantum states Mixing in [B]:

$$|M;1,0\rangle = \quad c\,|M;\uparrow\downarrow\rangle + s\,|M;\downarrow\uparrow\rangle$$

$$|M;0,0\rangle = -s\,|M;\uparrow\downarrow\rangle + c\,|M;\downarrow\uparrow\rangle$$

- Changed decay widths

$$\Gamma_t(B_z) = \Gamma_{o-Ps\to 3\gamma} + \Gamma'\left(\frac{\mu_B B_z}{\Delta E_{hyperfine}}\right)^2$$

Positronium

$$\Gamma_s(B_z) = \Gamma_{p-Ps\to 2\gamma} - \Gamma'\left(\frac{\mu_B B_z}{\Delta E_{hyperfine}}\right)^2$$

- [B=1T]: (30% ortho-Ps → 3γ disappear)

this is called the "Quenching" of decay.

- **30% J/Ψ → l^+l^- in B=10^{15}T can disappear, QGP signal** is affected.

Magnetic moments of Baryons [Quarks]

SU(6)

baryon	m [MeV]	quarks	μ_{exp}	δ_μ	μ
p	938.3	du-u	2.79	0	2.79
n	939.6	du-d	-1.91	0	-1.91
Λ	1115	du-s	-0.613	0	0.613
Σ^+	1189	us-u	2.46	9 %	2.67
Σ^-	1197	ds-d	-1.16	6 %	-1.09
Ξ^o	1315	us-s	-1.25	13%	-1.43
Ξ^-	1322	ds-s	-0.65	24%	-0.49
Ω^-	1672	sss	-2.02	9 %	-1.84
Δ^{++}	1232	uuu	6.14	(9%)	5.56
Δ^+	1232	uud	2.7	(1%)	2.73

$\mu^* = \mu_s$

$\mu^* = (4\mu_a - \mu_b)/3$

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spin **3/2**

$\mu^* = \sum \mu_q$

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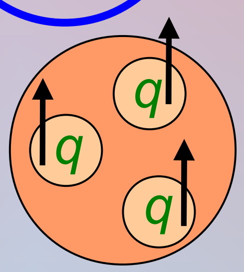


Quark magnetic moments:

quark	Q	μ_q [μ_N]	m^* [MeV]
u	2/3	1.852	338
d	-1/3	-0.972	322
s	-1/3	-0.613	510

Agreement:

$$\mu_q = \frac{\hbar Q}{2m^*}$$

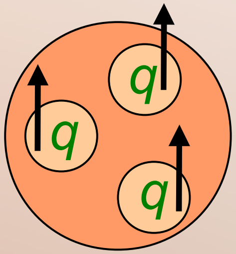
constituent quark mass

Magnetic moments of ***Vector mesons***:

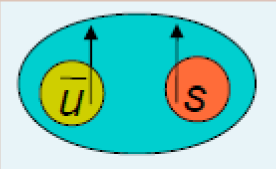
Observe: spin **3/2** baryons

			μ_{exp}	δ_μ	μ
Ω^-	1672	sss	-2.02	9 %	-1.84
Δ^{++}	1232	uuu	6.14	(9%)	5.56
Δ^+	1232	uud	2.7	(1%)	2.73

$\mu^* = \sum \mu_q$



Vector mesons: spin 1 (L=0)



K^{*-}

charged open-flavor $\mu^* = \sum \mu_q$

$$\mu_q = \frac{\hbar Q}{2m^*}$$

m^*_b=4730

m^*_c=1510

	ρ^-	K^{*+}	D^{*-}	D_s^{*-}	B^{*-}
m [MeV]	770	892	2010	2112	5325
$q\bar{q}$	$d\bar{u}$	$u\bar{s}$	$d\bar{c}$	$s\bar{c}$	$b\bar{u}$
μ [μ_N]	-2.82	2.46	-1.37	-1.02	-1.92

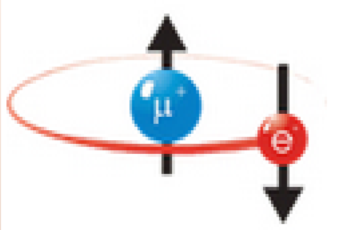
Agrees with L-QCD: Lee et al. PoS (LATTICE 2007) 151.

quark	Q	μ_q [μ_N]
u	2/3	1.852
d	-1/3	-0.972
s	-1/3	-0.613
c	2/3	0.404
b	-1/3	-0.066

–> $\mu_c = -2\mu_s / 3$

–> $\mu_b = \mu_s / 9$

Using Analogy with Muonium:



- Muonium = (μ^+e^-) μ_μ , μ_e

  (*triplet*) and (***singlet***) state

- Vector mesons

  –> ***Triplet state*** D^*, B^*, K^*

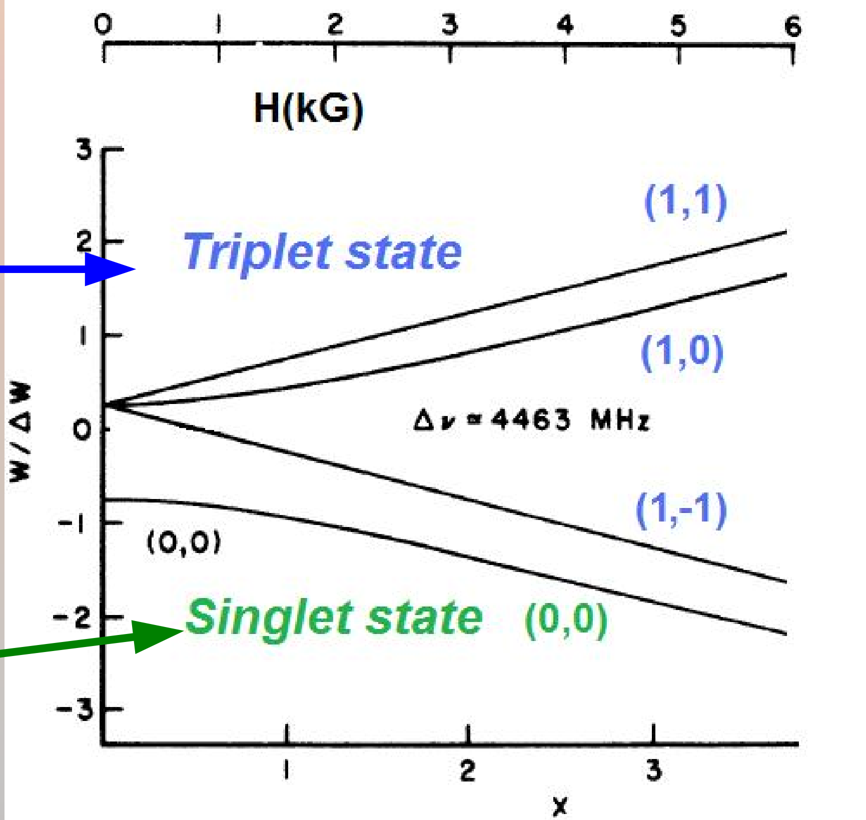
  ($\mu_{\mu,e}$ <–> $\mu_{c,d,s,u}$)

- *Pseudoscalar* mesons

  D^0(uc'), ***B***^{0}(db'), ***B***$_s$(bs'), ***K***^{0}(ds')

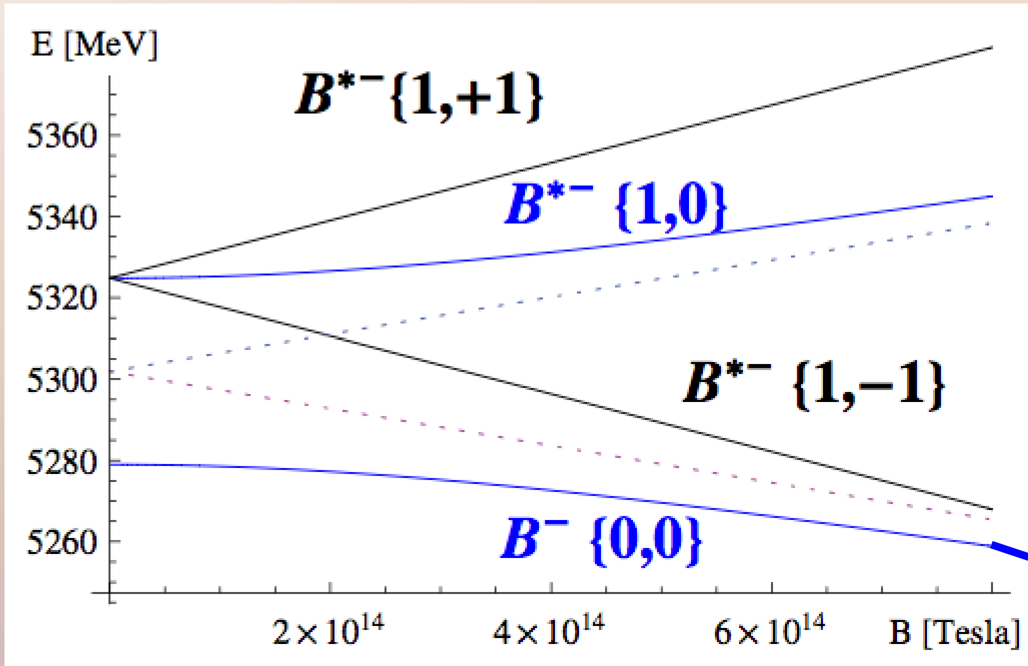
  no magnetic moment

  only polarizability



Energy-level diagram for muonium in 1^2S ground state in a magnetic field

Open-flavor *Vector mesons* in [B]



$|\uparrow\uparrow\rangle$ **–> *Magnetic moment***

–> *Magnetic polarizabiliy*

$$\Psi_o^+ = \frac{c_\alpha + s_\alpha}{\sqrt{2}}|\uparrow\downarrow\rangle + \frac{c_\alpha - s_\alpha}{\sqrt{2}}|\downarrow\uparrow\rangle$$

$|\downarrow\downarrow\rangle$ **–> *Magnetic moment***

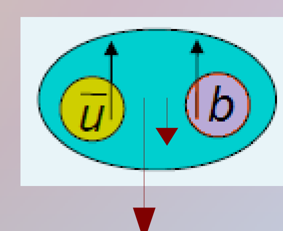
–> *Magnetic polarizabiliy*

$$\Psi_p^- = \frac{c_\alpha - s_\alpha}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{c_\alpha + s_\alpha}{\sqrt{2}}|\downarrow\uparrow\rangle$$

–> ***charged*** *Vector mesons*:

Magnetic moment: charged open-flavor J^P=1$^-$ mesons.

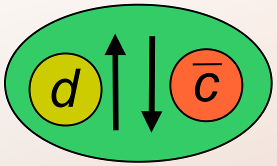
	ρ^-	K^{*+}	D^{*-}	D_s^{*-}	B^{*-}
m [MeV]	770	892	2010	2112	5325
$q\bar{q}$	$d\bar{u}$	$u\bar{s}$	$d\bar{c}$	$s\bar{c}$	$b\bar{u}$
μ^* [μ_N]	-2.82	2.46	-1.37	-1.02	-1.92



$\mu^* = \sum \mu_q$

$$\mu_{B*} = \mu_{\boldsymbol{u}} + \mu_{\boldsymbol{b}} = 1.9\mu_N$$

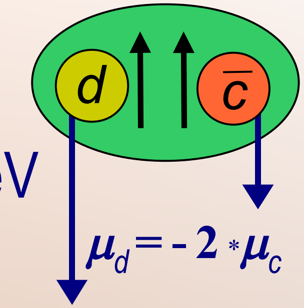
Similar to μ_{neutron}

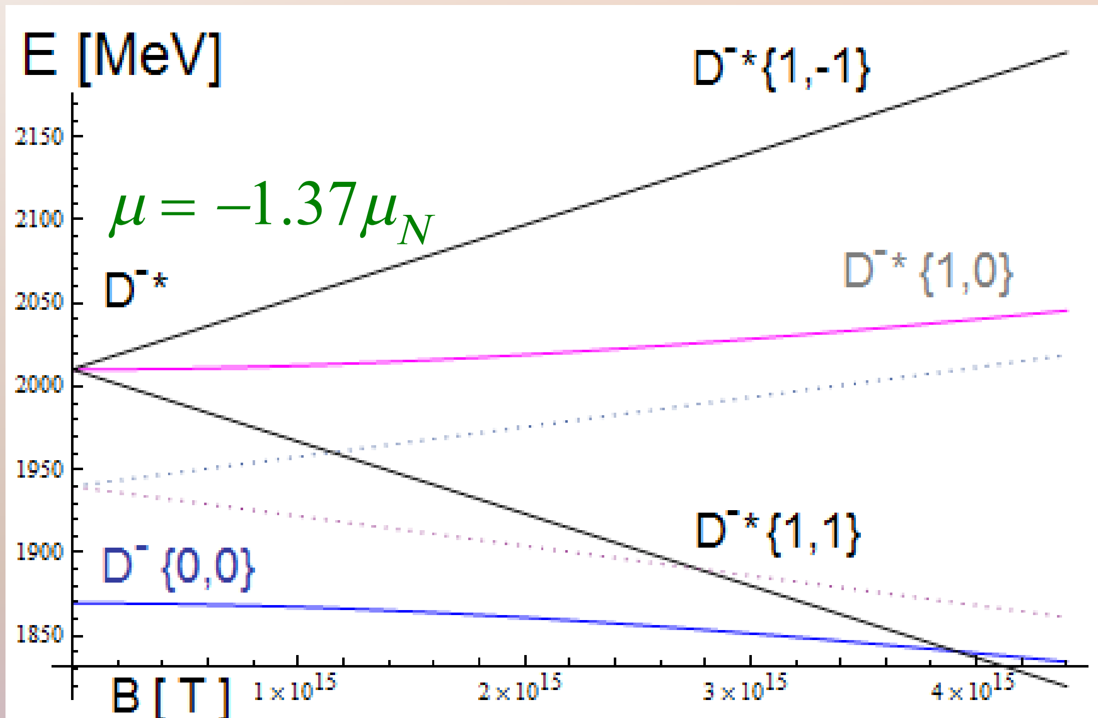


D^- meson magnetic behavior D^{-*}

(1869) MeV

(2010) MeV





D^- $c\tau = 312\ \mu m$

$\Gamma_{D^{-*}} =$ 96 keV, $c\tau = 2070$ fm

Our simple calculation: $\mu = \sum \mu_q$

D^{*0}	ρ^-	K^{*+}	D^{*-}
2007 MeV	770	892	2010
$c\bar{u}$	$d\bar{u}$	$u\bar{s}$	$d\bar{c}$
-1.44 μ_N	-2.82	2.46	-1.37

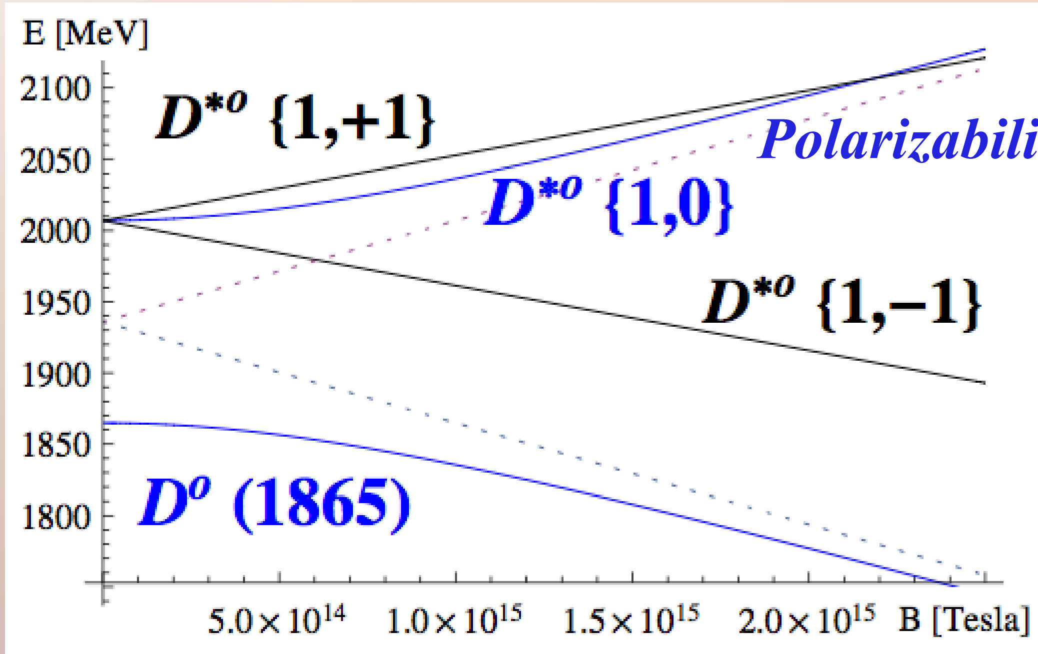
PHYSICAL REVIEW C VOLUME 59, NUMBER 3 MARCH 1999

Electromagnetic form factors of light vector mesons

F. T. Hawes M. A. Pichowsky

Calculated static properties of vector mesons include the charge radii and magnetic moments $\langle r^2_{\rho+}\rangle^{1/2} = 0.61$ fm, $\langle r^2_{K^{*+}}\rangle^{1/2} = 0.54$ fm, and $\langle r^2_{K^{*0}}\rangle = -0.048$ fm^2 and $\mu_{\rho+} = 2.69$, $\mu_{K^{*+}} = 2.37$, and $\mu_{K^{*0}} = -0.40$. The calculated static limits of the ρ-meson form factors are similar to those obtained from light-front quantum mechanical calculations.

Open-flavor NEUTRAL *mesons* in [B]



$$\Psi_o^+ = \frac{c_\alpha + s_\alpha}{\sqrt{2}}|\uparrow\downarrow\rangle + \frac{c_\alpha - s_\alpha}{\sqrt{2}}|\downarrow\uparrow\rangle$$

Polarizability *[induced magnetic moment]*

$$\langle\Psi_o^+|\hat{\mu}_{c\bar{u}}|\Psi_o^+\rangle = -(|\mu_c|+|\mu_u|)\sin(2\alpha)$$

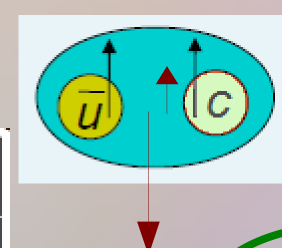
–> ***Magnetic moment*** $E = -\mu \cdot B$

–> ***Magnetic polarizability:***

induced magnetic moment is LARGER than STATIC $\mu_{D^{o*}}$

–> ***neutral*** <u>*Vector mesons*</u>:

	B^{*o}	B_s^{*o}	K^{o*}	D^{o*}
m [MeV]	5325	5415	896	2007
$q\bar{q}$	$d\bar{b}$	$s\bar{b}$	$d\bar{s}$	$c\bar{u}$
μ^* $[\mu_N]$	-0.9	-0.5	-0.3	-1.4



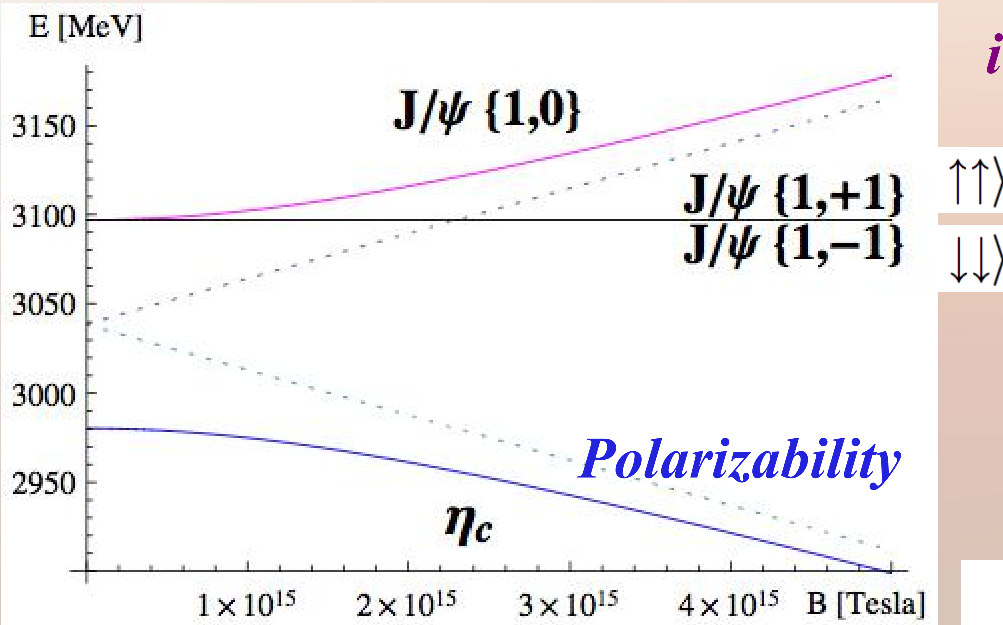
$\mu^* = \sum \mu_q$

D^{0*}

$$\mu_{D^{o*}} = |\mu_c| - |\mu_u| = -1.4\mu_N$$

For $|\mu_c| = |\mu_u| \rightarrow \mu = 0$ (J/Ψ, Υ)

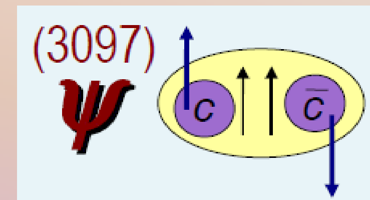
Hidden flavour+Heavy = ***Quarkonium***



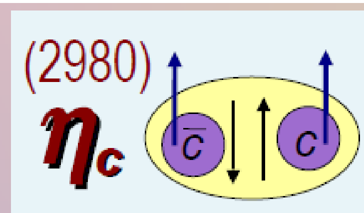
induced magnetic moment $\mu^* = -2\mu_c$

–> *Magnetic moment* **= 0**

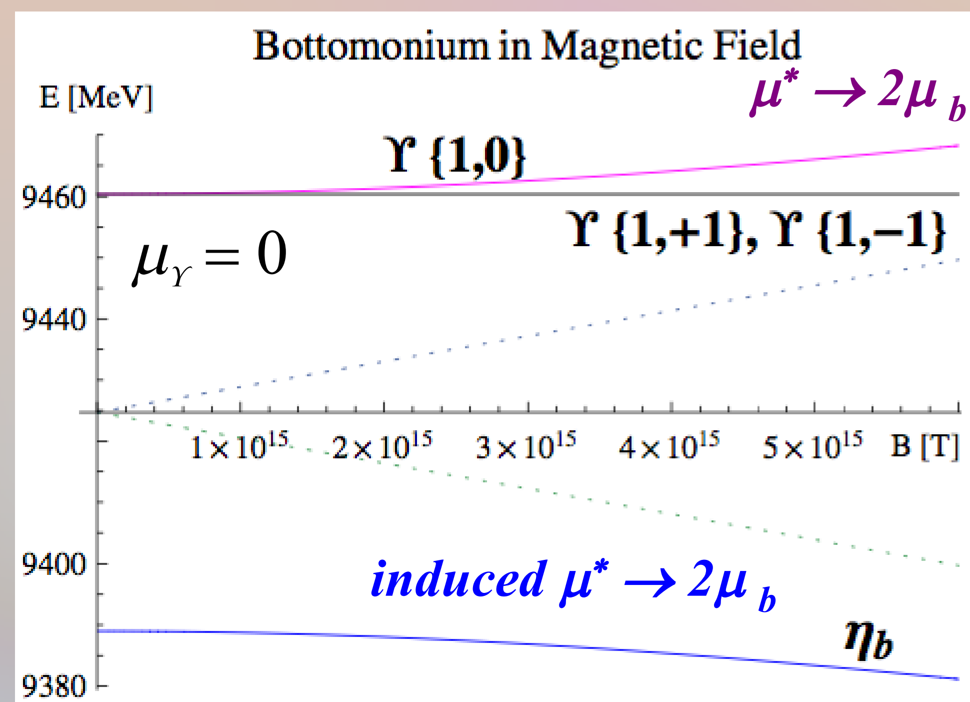
$$\mu_\psi = |\mu_c| - |\mu_c| = 0$$



B → **large**: $\mu^* \to 2\mu_c$



$$\Psi_p^- = \frac{c_\alpha - s_\alpha}{\sqrt{2}} |\uparrow\downarrow\rangle - \frac{c_\alpha + s_\alpha}{\sqrt{2}} |\downarrow\uparrow\rangle$$



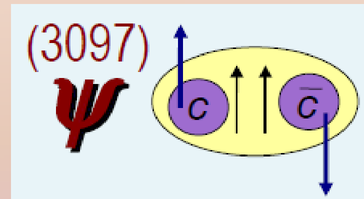
QUARKONIUM ≈ POSITRONIUM

- *mixing of* ***ortho ↔ para*** *states*
- *quenching of* ***ortho-Ps*** *decay*

Quarkonium ↔ Leptonium

J/Ψ , ϒ(9460), φ(1020) **e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$**

- cc', bb', ss'

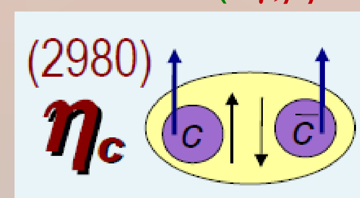


para-cc' = η_c ortho-**cc'** = **J/Ψ**

$c\tau$ = 2100 fm (3γ,μμ)

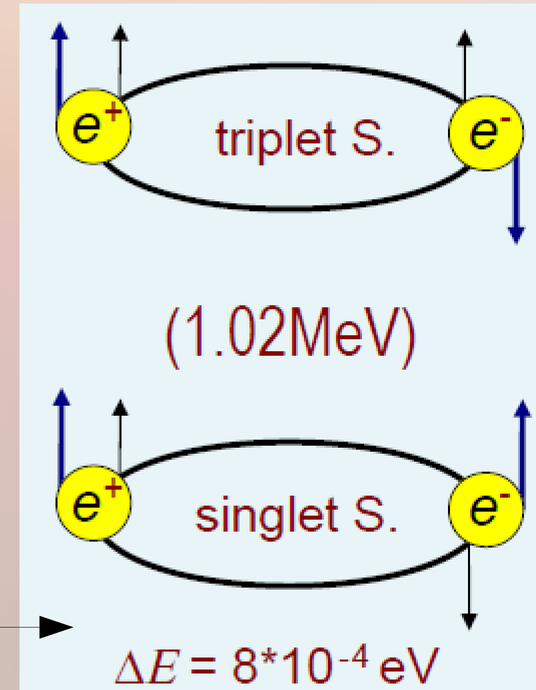
ΔE =117 MeV

$c\tau$ = 6.9 fm (2γ,ρρ...)



$\tau_o / \tau_p = 3{*}10^2$

- Positronium e^+e^- (**1S**)



ortho-**Ps** (J=1, mz=1,0,-1) para-**Ps** (J=0)

- lifetimes: **142ns** (3γ,5γ) and **0.12ns** (2γ,4γ)

$\tau_o / \tau_p = 1.2{*}10^3$

MAGNETIC QUENCHING

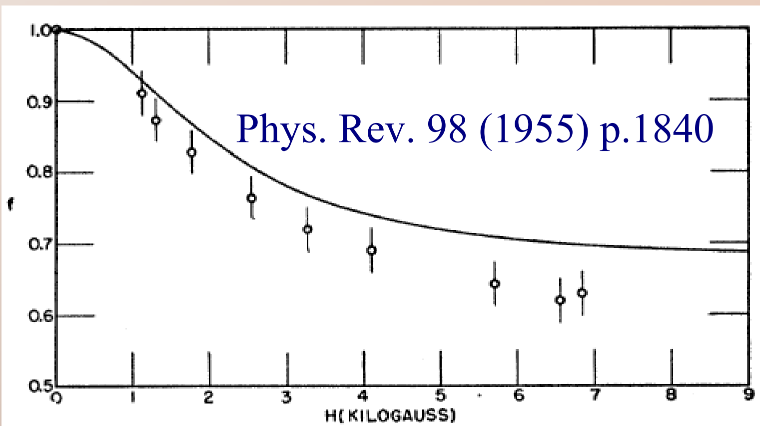
ϒ OF J/Ψ

ortho-Quarkonium **DECAY**

Positronium: discovered @MIT (1951)

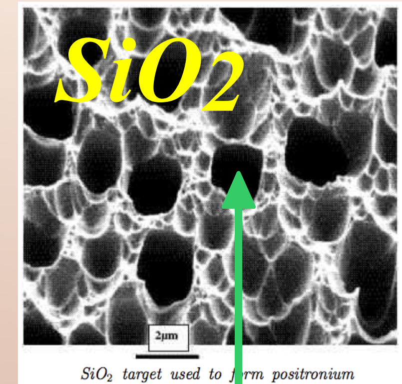
Predicted in (1934)

- 1955: **Magnetic Quenching observed**

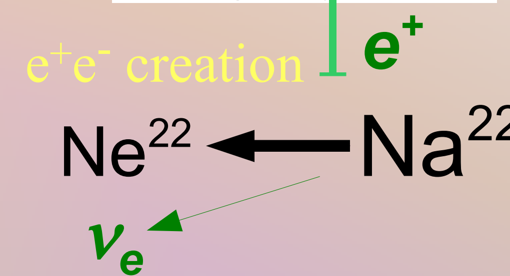


fraction, f, of orthopositronium which decays by three-q annihilation as function of magnetic field.

30% of $\gamma\gamma\gamma$ decays



in magnetic field: 1 Tesla

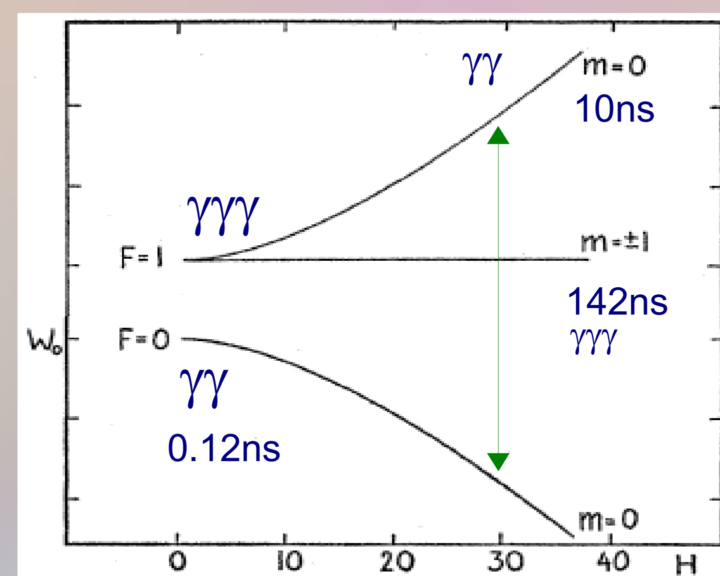


3γ decays disappear

(replaced by 2γ)

$$\Psi_p^- = \cos(\alpha)\Psi_p - \sin(\alpha)\Psi_o$$

$$\Psi_o^+ = \cos(\alpha)\Psi_o + \sin(\alpha)\Psi_p$$



ortho-Positronium: decays –> $\gamma\gamma$

- similarly: K_L –> $\pi\pi$ [CPv]

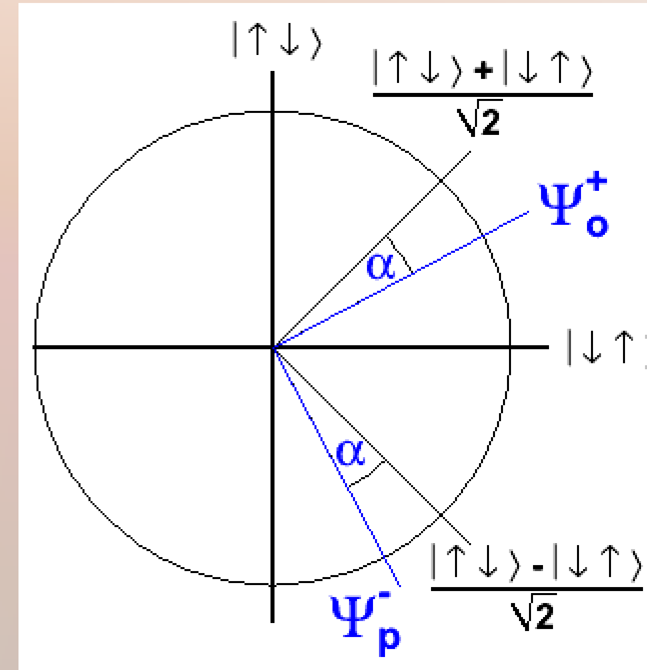
PHYSICAL REVIEW VOLUME 98, NUMBER 6 JUNE 15, 1955

Static Magnetic Field Quenching of the Orthopositronium Decay

V. W. HUGHES, S. MARDER, AND C. S. WU
Columbia University, New York, New York

ortho-Ps {1,0} (e^+e^-) –> 2γ

In the presence of a magnetic field the $M=\pm1$ magnetic substates of orthopositronium are still pure ortho-states, and will decay by the three quantum annihilation characteristic of orthopositronium decay. On the other hand, the $M=0$ state of orthopositronium has a small admixture of para-state due to the interaction with the magnetic field, and hence can decay either by three-quantum annihilation or by two-quantum annihilation. The relative probabilities of these two modes of decay depend of course, on the



- Mixing in [B]:

$$|M;1,0\rangle = \quad c\,|M;\uparrow\downarrow\rangle + s\,|M;\downarrow\uparrow\rangle$$

$$|M;0,0\rangle = -s\,|M;\uparrow\downarrow\rangle + c\,|M;\downarrow\uparrow\rangle$$

for B=0 $c^2 = s^2 = 1/2$

in [B] orto-Ps (J=1) and para-Ps (J=0) states get Mixed together

$$X = 2|\mu_e|B/\Delta E_{hf}$$

- 30% decays affected. J/Ψ : B=10^{15}T

$$s = \frac{1}{\sqrt{2}}\left[1 - \frac{X}{\sqrt{1+X^2}}\right]^{\frac{1}{2}}, \quad c = \frac{1}{\sqrt{2}}\left[1 + \frac{X}{\sqrt{1+X^2}}\right]^{\frac{1}{2}}.$$

$J/\Psi\{1,0\}$ <— MIXING —> $\eta_c\{0,0\}$

$\mu_c = 0.4 * \mu_N = \mu_e / 4500$ $X = 2|\mu_e|B/\Delta E_{hf}$ $\Delta E_{cc} = \Delta E_{ee} * 1{,}4\ 10^{11}$

1) opens $\eta_c \to e^+e^-$ channel (directly to dilepton)

2) opens $J/\Psi \to \gamma\gamma$, gg channel (C-parity OK: $\gamma\gamma$-γ^*)
virtual

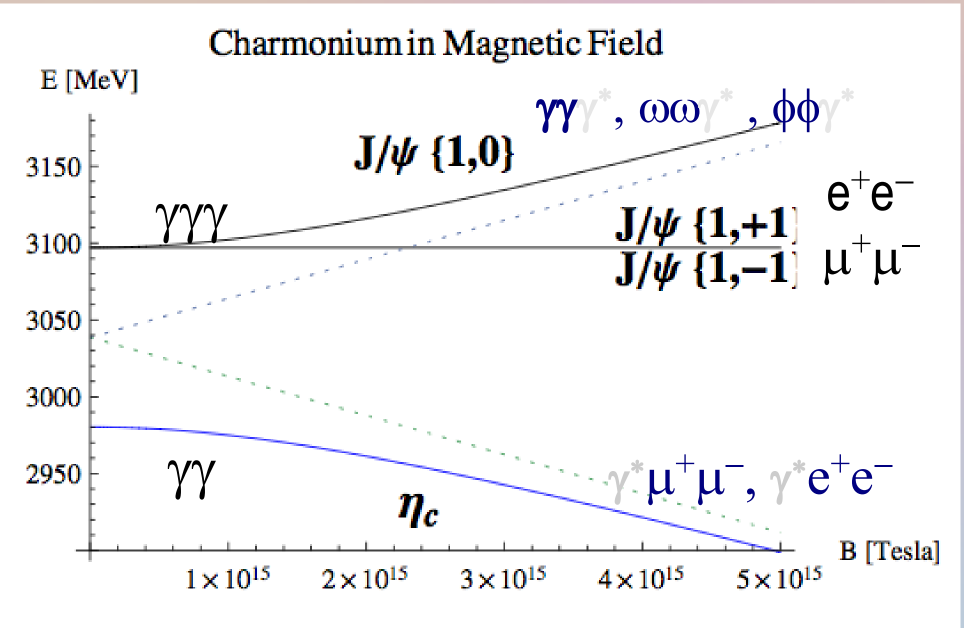
3) $\Gamma_{J/\Psi}$ increases: shorter "cτ"

However:

(LHC)
- STATIC **strong B** needed: 10^{15} T
- RHIC: **$B=10^{14}$ T** short time: **0.1fm**

J/Ψ: cτ =**2100fm** η_c: cτ =**7fm**

Υ: cτ =**3400fm** –> ***small effect***



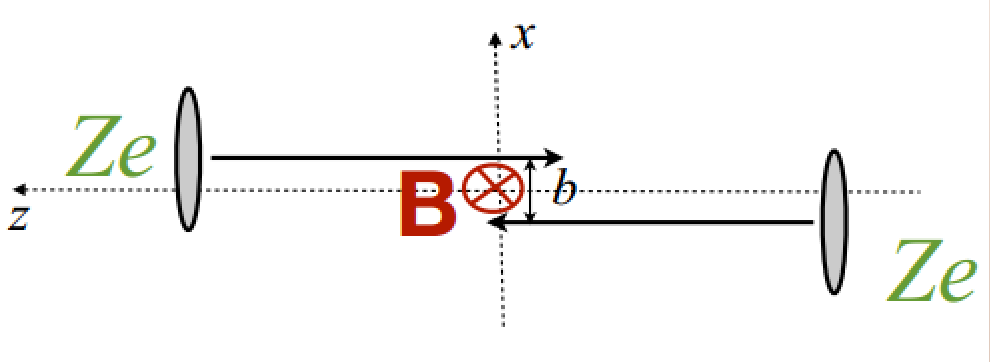
Magnetic Fields in Au+Au / Pb+Pb

LHC: **B ≈ 4.10^{15}T**

RHIC: **B ≈ 3.10^{14}T**

$eB \approx 3m_\pi^2$

PHYSICAL REVIEW C **85**, 044907 (2012)



PHYSICAL REVIEW C **83**, 054911 (2011)

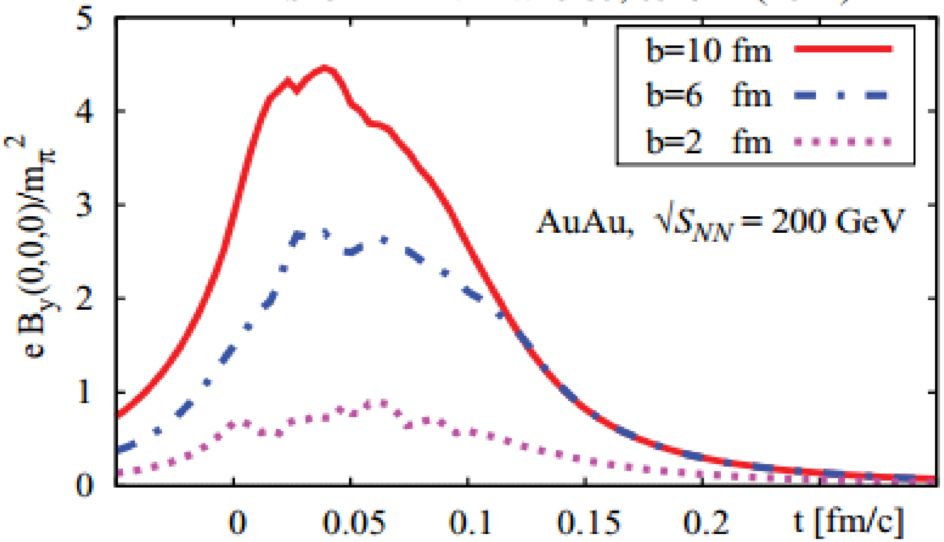
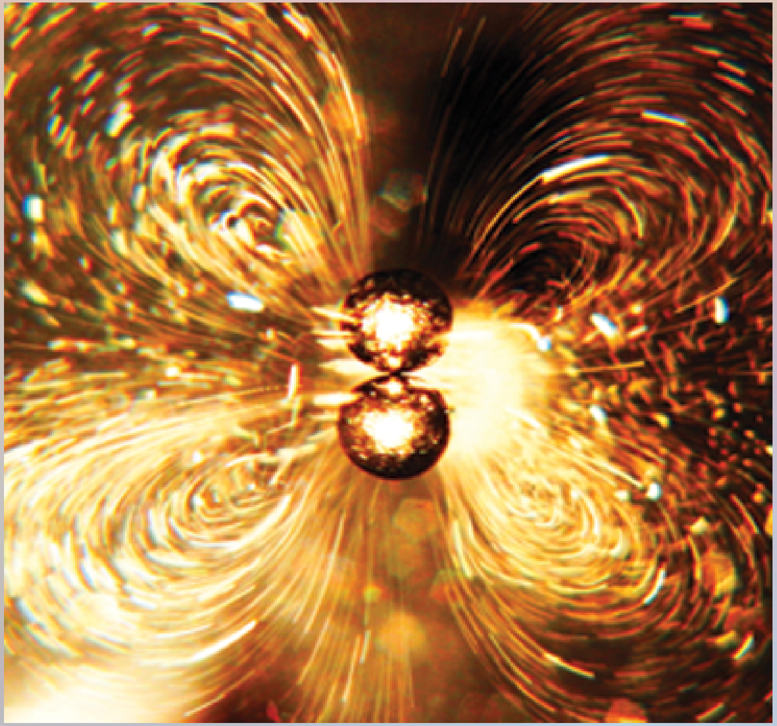


FIG. 13. Impact parameter dependence of the magnetic field. Au + Au collisions $\sqrt{s_{NN}}$ = 200 GeV.



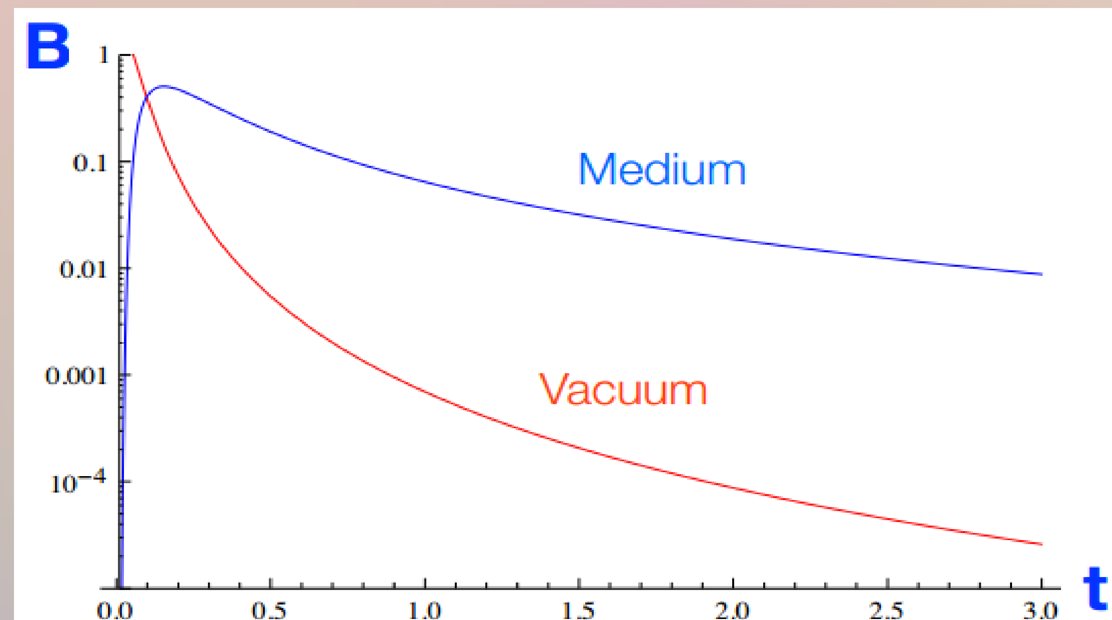
PHYSICAL REVIEW C **82**, 034904 (2010)

Kirill Tuchin

Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA and

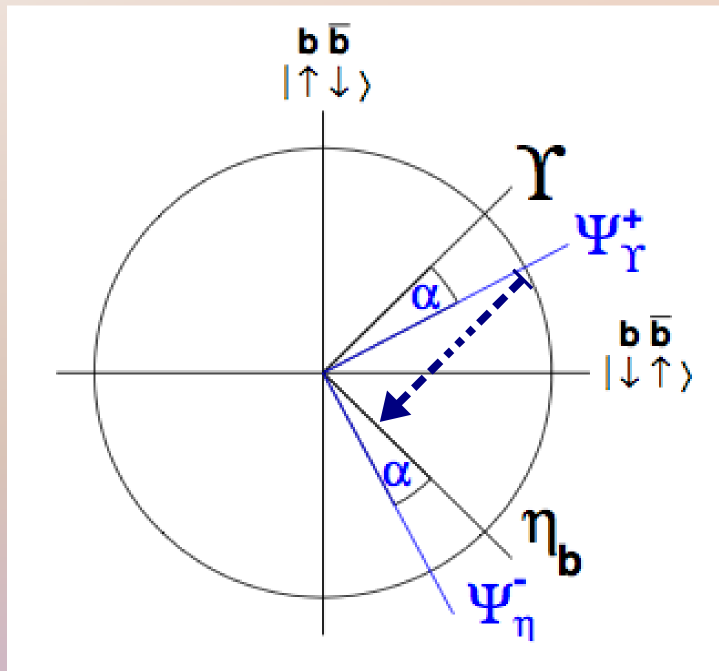
We study the synchrotron radiation of gluons by fast quarks in strong magnetic field produced by colliding relativistic heavy ions. We argue that due to high electric conductivity of plasma, the magnetic field is almost constant during the entire plasma lifetime. We calculate the energy loss due to synchrotron radiation of gluons by fast quarks. We find that the typical energy loss per unit length for a light quark at the Large Hadron Collider

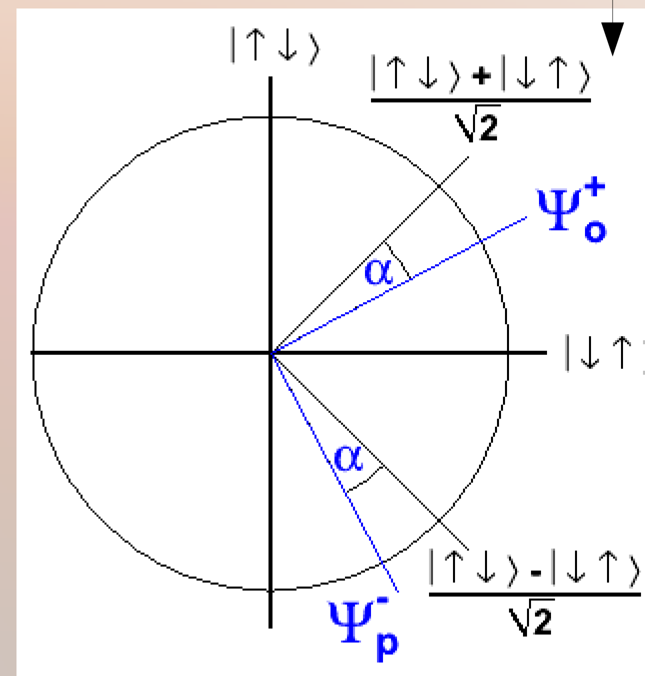
–> Plasma keeps [B] fields: QGP is elmag. plasma



in QED plasma → stabilization of Magnetic Fields

Quarkonium (**J/Ψ** , **Υ**) and Positronium mixing of states in **magnetic field**.





$$\Psi^+_\Upsilon = \cos(\alpha)\Upsilon + \sin(\alpha)\eta_b$$

(82%)

(2.4%) e^+e^- ggg gg

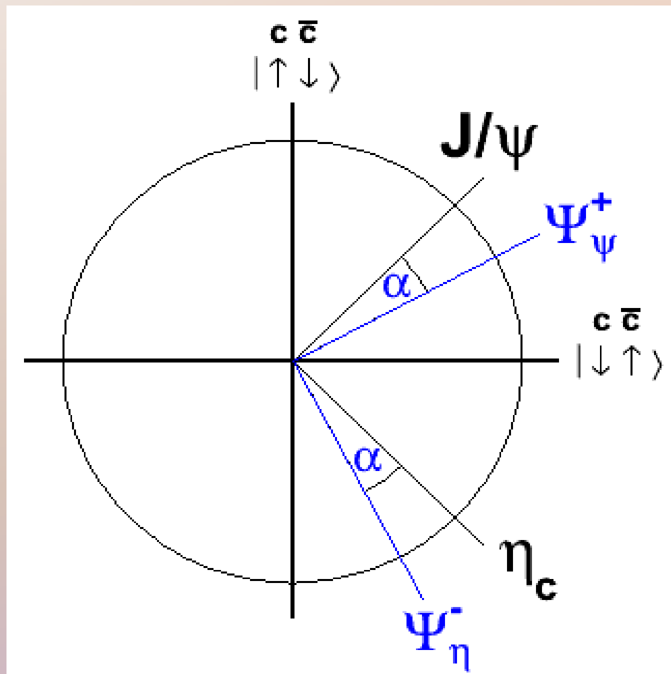
In static field B= 5*10^15 Tesla

$$\Psi^+_o = \cos(\alpha)\Psi_o + \sin(\alpha)\Psi_p$$

$\gamma\gamma\gamma$ $\gamma\gamma$

in field B = 1 Tesla

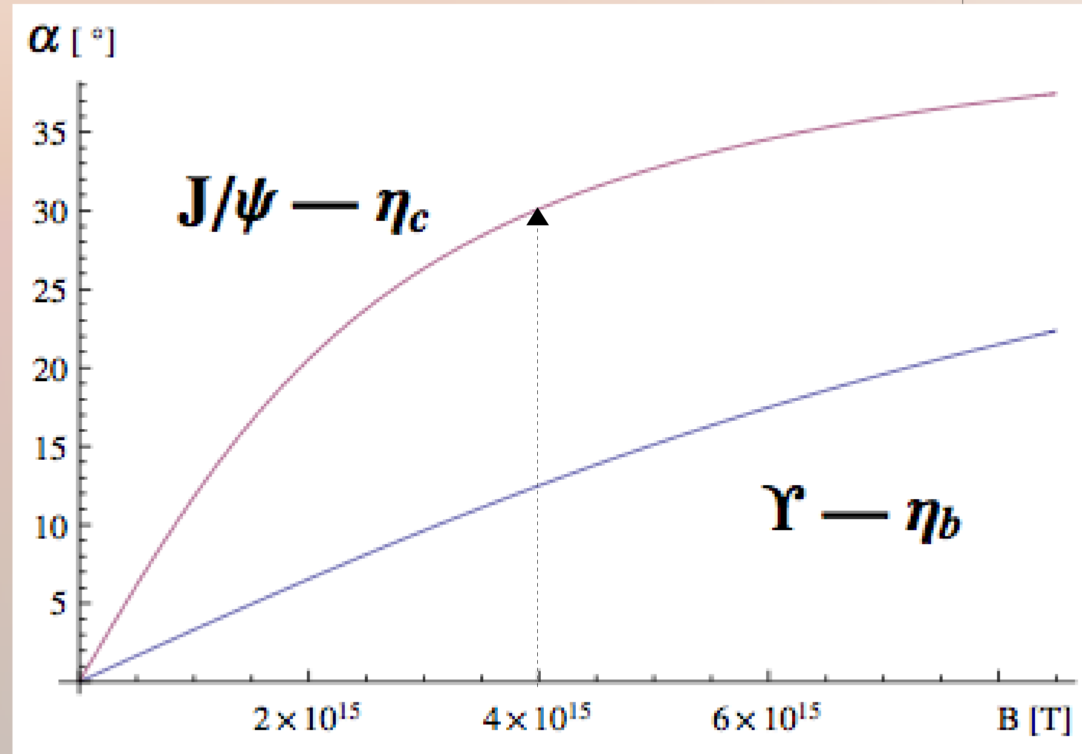
Charmonium ($\mathbf{J/\Psi} \longleftrightarrow \boldsymbol{\eta_c}$) mixing quantum state superposition in [B].



$$\Psi^+_{J/\psi} = \cos(\alpha)\,\mathbf{J/\psi} + \sin(\alpha)\,\eta_c$$

(64%)

(6%) $e^+e^-\mu^+\mu^-$ ggg gg

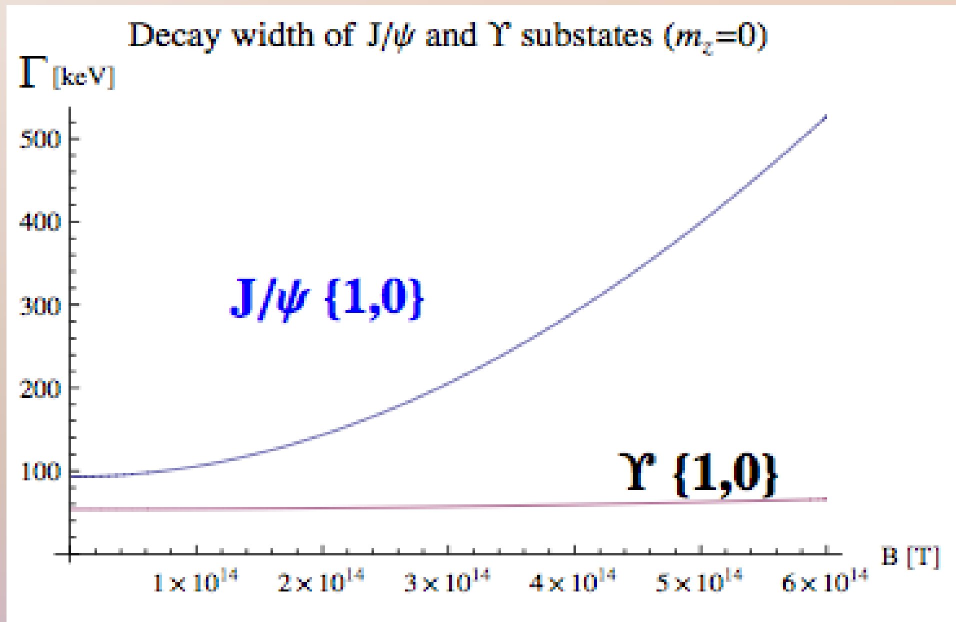


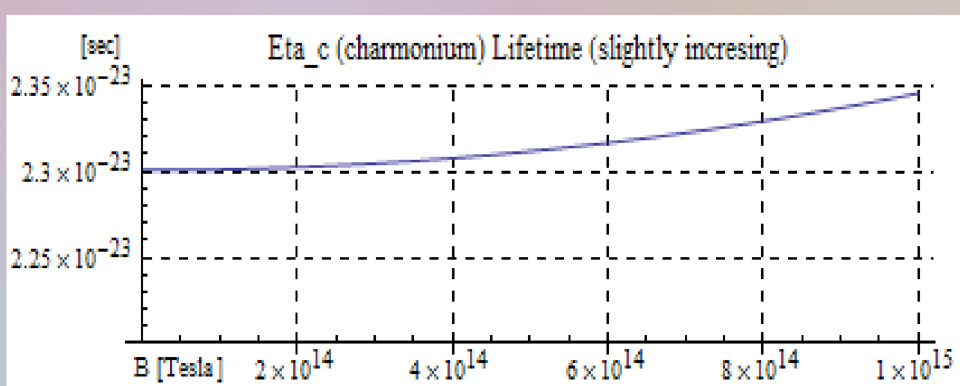
Angle α for the mixing of quarkonium states in magnetic fields: $\tan(\alpha) = x/(1+\sqrt{1+x^2})$.

$$x = 2\mu_{12}B/\Delta E_{hf}$$

in static field B= 4*10^{14} Tesla α = 30° for J/Ψ and 12° for ϒ.

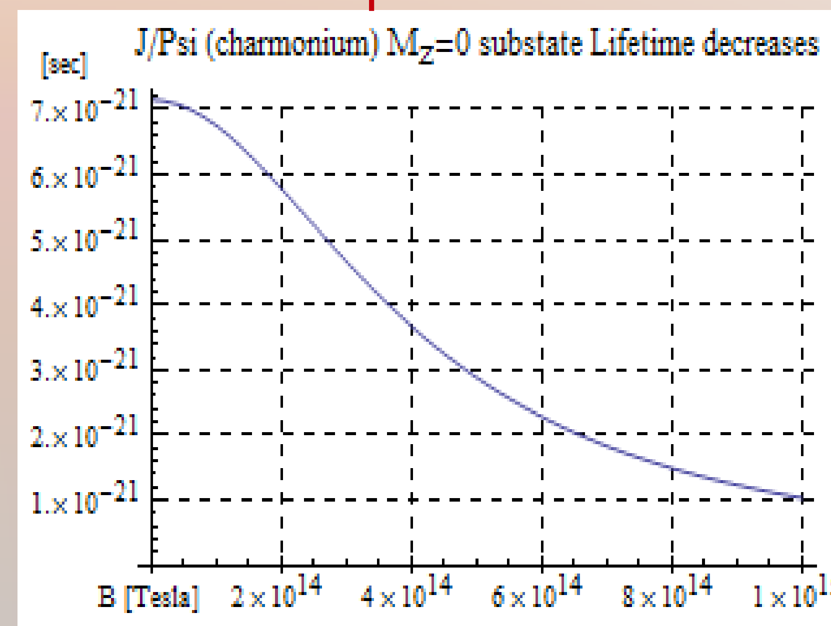
Decay width of **J/Ψ** and **Υ** (increasing) due ⟶ **gg** channel.





2100 fm/c

Lifetime of J/ψ is reduced



400 fm/c

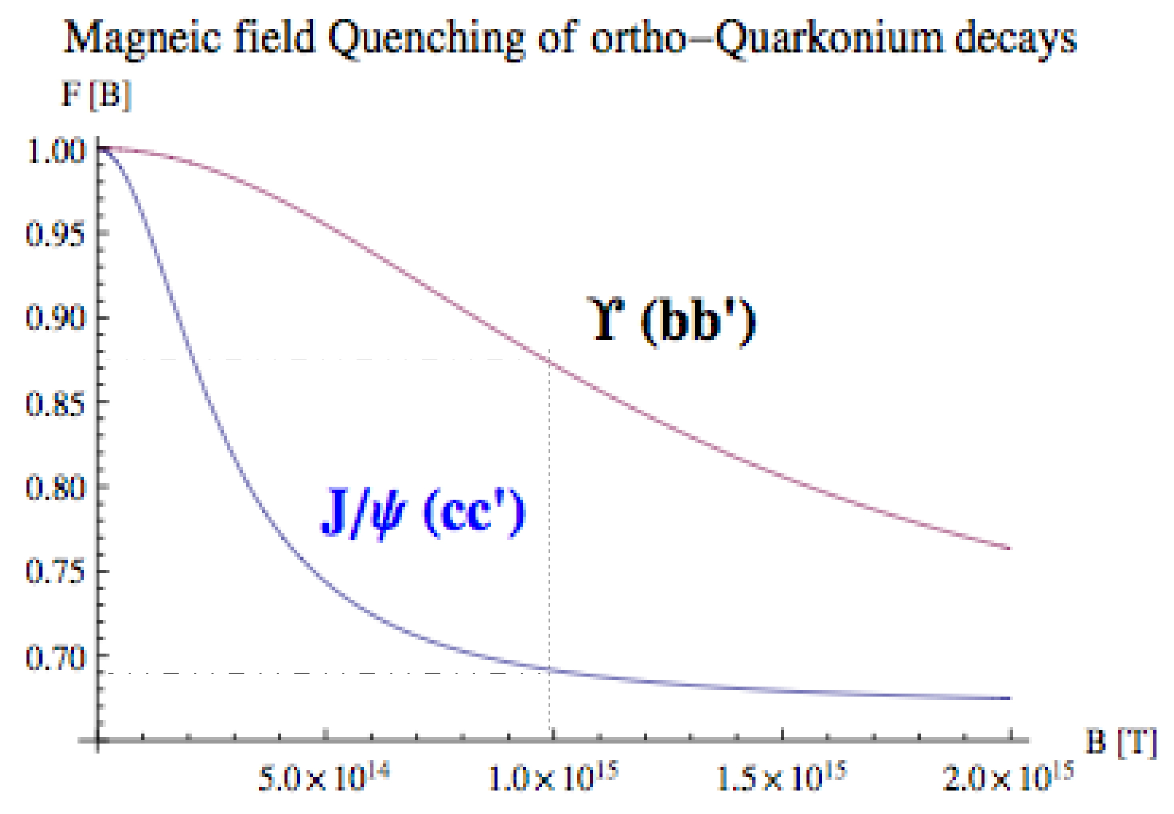
$$\Gamma_t(B_z) = \Gamma_{o-Ps\rightarrow 3\gamma} + \Gamma'\left(\frac{\mu_B B_z}{\Delta E_{hyperfine}}\right)^2$$

$$\Gamma_s(B_z) = \Gamma_{p-Ps\rightarrow 2\gamma} - \Gamma'\left(\frac{\mu_B B_z}{\Delta E_{hyperfine}}\right)^2$$

Fraction of **J/Ψ** and **ϒ** decays via <u>original</u> channels (also e^+e^-, $\mu^+\mu^-$).

At B = 10^{15} Tesla

- **30%** of $J/\psi \rightarrow e^+e^-$ decays are **quenched** (missing from e^+e^- spectrum)
- **12%** of $\Upsilon \rightarrow \mu^+\mu^-$ missing = quenched.

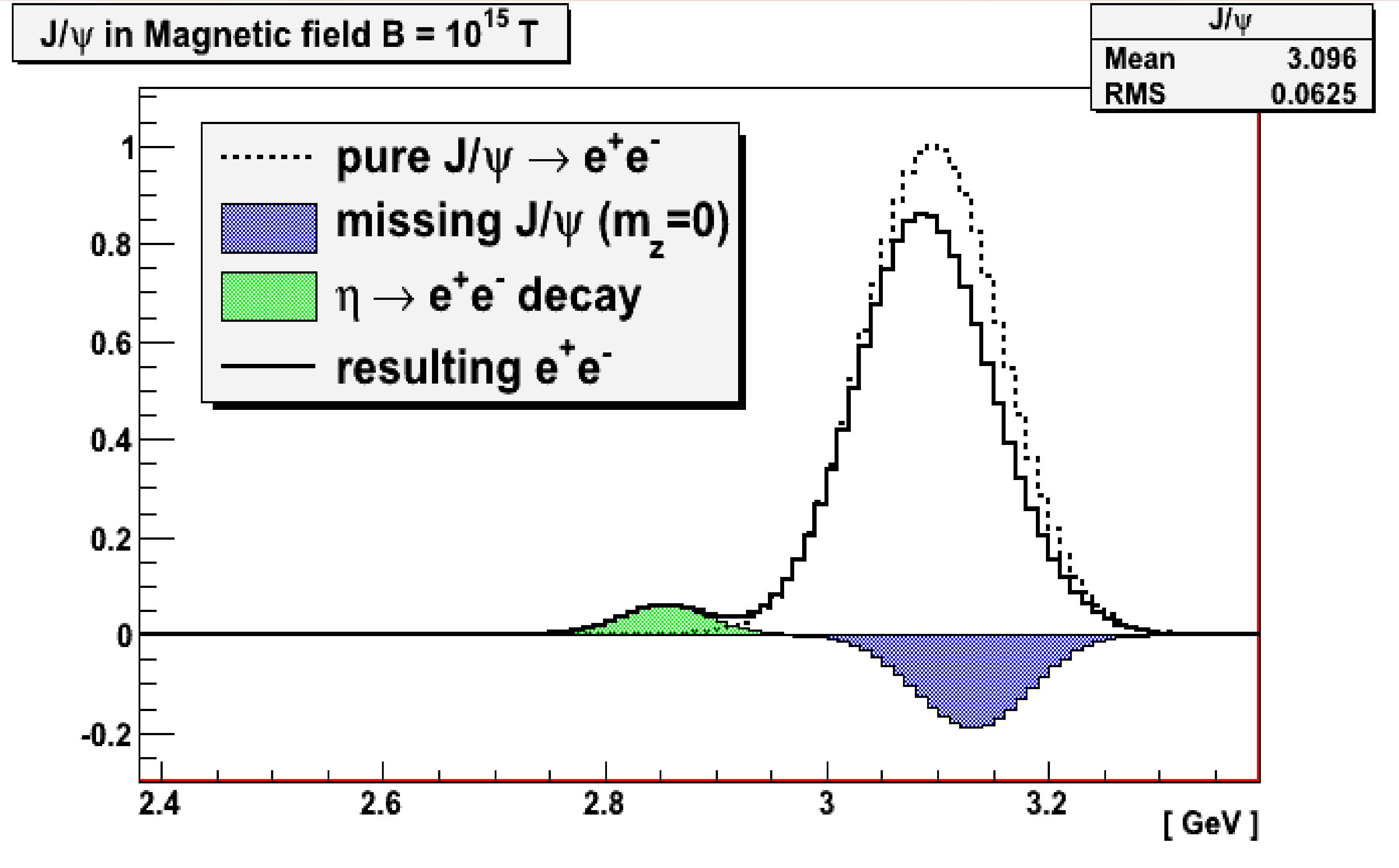


Fraction of J/Ψ and Υ particles decaying to (l^+l^-)

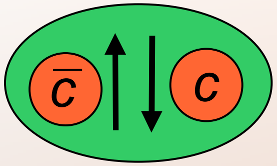
*Static magnetic field is assumed.

Magnetic Field Influence

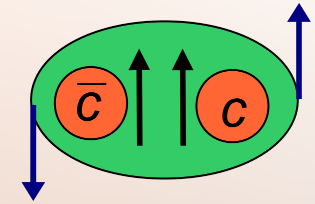
on dilepton spectrum from J/Ψ



* Resulting e^+e^- Peak(J/Ψ) has its Mass shifted down + little **bump (η_c).**



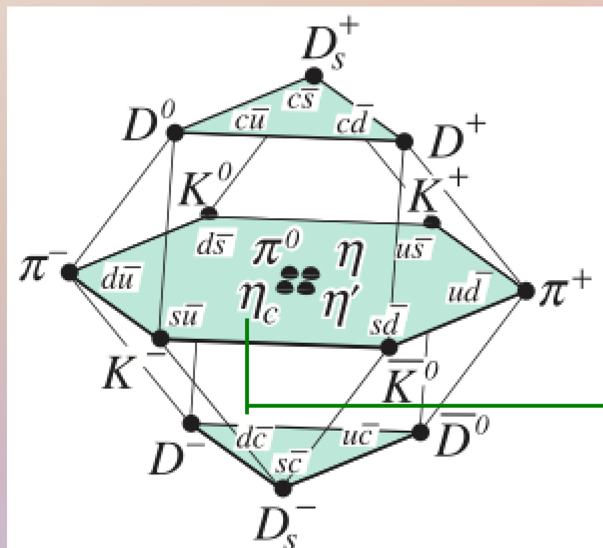
MESON MULTIPLETS



(mixing in magnetic fields)

η' (958) ← $s\bar{s}$ → φ (1019)

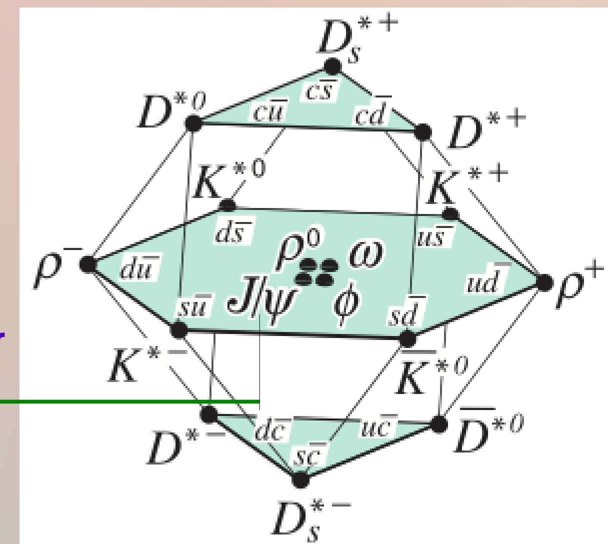
$\mu_{(qq)} = 0$ $\qquad$ $|\mu_{(qq)}| > 0$



π^o $(u\bar{u} - d\bar{d})$ ρ^o

η $(u\bar{u} + d\bar{d})$ ω

η_c $(c\bar{c})$ J/Ψ



mixing of states

η_b(9391) ← $(b\bar{b})$ → Υ(9460)

ϕ(1020) ⟵ CONNECTION ? ⟶ η'(958)

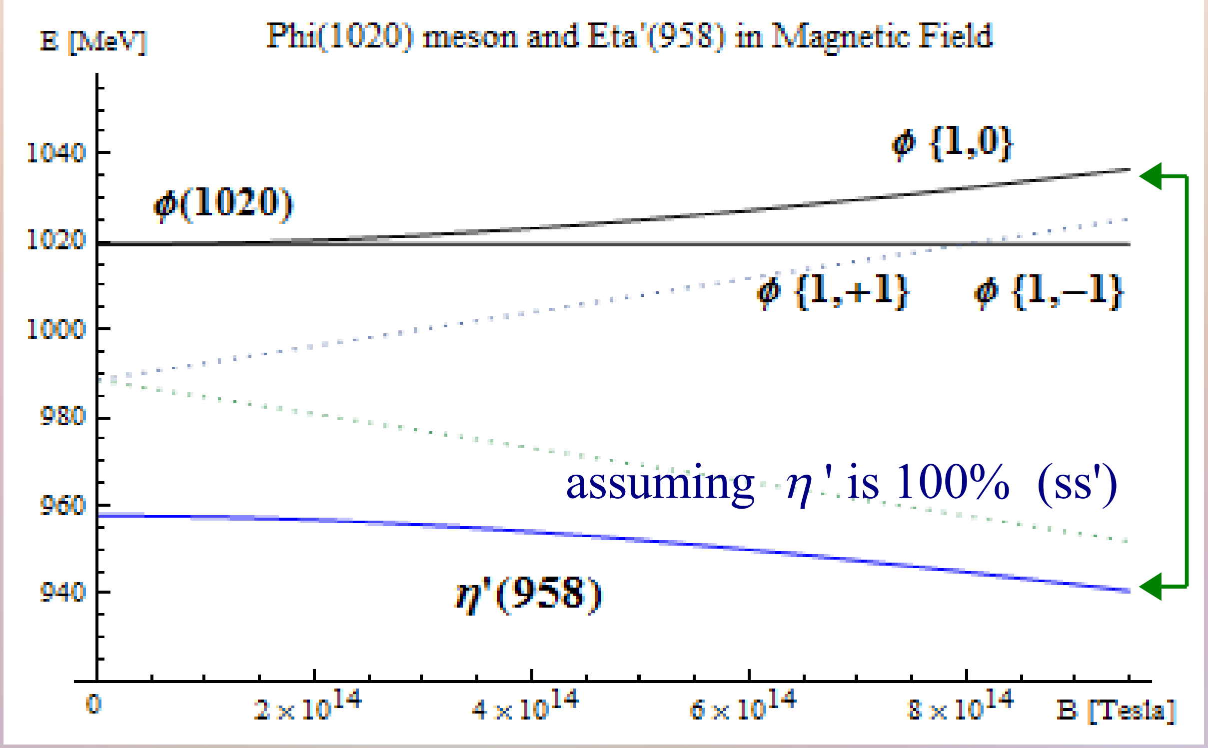
[99% ss'] ortho-para state **mixing** [66% ss']

$\tau_\varphi / \tau_{\eta'}$

is opposite to

$J/\Psi \leftrightarrow \eta_c$

$\Upsilon \leftrightarrow \eta_b$



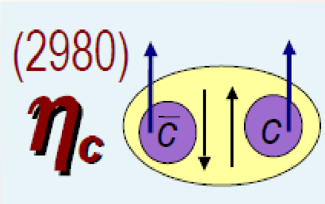
φ: cτ=46fm/c η': cτ=990fm/c

φ: Γ=4.3MeV η': Γ=199 keV

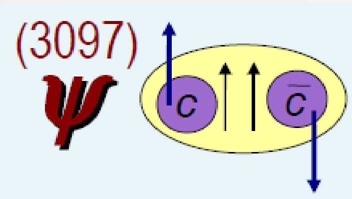
If mixing happens:

–> η': starts decaying e^+e^-

–> $\Gamma_{\eta'}$ increase (bump of e^+e^-)



CONCLUSIONS



1) Heavy Quarkonium <––> Positronium

- mixing of **$\eta_c \leftrightarrow$ J/Ψ** states in static B = [5∗10^{14} Tesla]

  $\eta_b \leftrightarrow \Upsilon$ (2∗10^{15} Tesla is required)

  –> reduced lifetime of **J/Ψ, ϒ (9460) (decay → 2 gluons)**

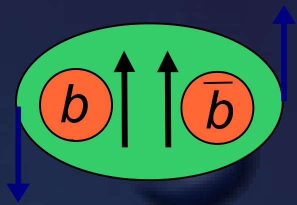
  –> missing **$\mu^+\mu^-$**, e^+e^- (J/Ψ, ϒ, max 30%): **QGP signal affected**

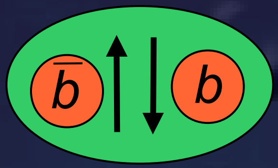
  –> direct **$\eta \rightarrow e^+e^-$** possible (small e^+e^- bumps below J/Ψ or ϒ)

2) Sensitive to Magnetic field duration in HIC

–> parton plasma gives longer [B] lifetime

3) **Mixing of** $\eta' \leftrightarrow \varphi$, $\eta \leftrightarrow \omega$, $\pi^o \leftrightarrow \rho^o$ possible





THANK YOU

for Your

ATTENTION

*Neglected: <qq'>[B] (chiral condensates)