Exam Subatomic Physics
Thursday, April 7 2011, 9:00-12:00

Gerco Onderwater

Rijksuniversiteit Groningen / KVI

Before you start, read the following:

- Write your name and student number on top of each page of your exam;
- Illegible writing will be graded as incorrect;
- This exam contains several appendices;
- Final grade = (10 + sum of points)/10;
- *Good luck!*

1 Allowed and Forbidden Processes (16 Points)

Examine the following processes carefully, and state for each one whether it is *possible* or *impossible*, according to the Standard Model. In the former case, state which interaction(s) is(are) responsible – strong, electromagnetic or weak; in the latter case, cite a conservation law that prevents it from occurring. When unambiguous, the charge is not indicated, thus γ, Λ, and n are neutral; p is positive, e is negative, *etc.* (1 point per process)

(a) $\pi^- \to \pi^0 + e^- + \bar{\nu}_e$

(b) $\gamma + p \to \pi^+ + n$

(c) $\Delta^- \to p + \pi^-$

(d) $\Lambda \to n + \gamma$

(e) $D^- \to K^+ + \pi^- + \pi^-$

(f) $\nu_\tau \to \nu_e + \gamma$

(g) $\pi^- + p \to n + e^+ + e^-$

(h) $Z^0 \to \gamma + \gamma$

(i) $\bar{p} \to \bar{n} + e^- + \bar{\nu}_e$

(j) $Z^0 \to \nu_e + \bar{\nu}_\mu$

(k) $e^- + \bar{\nu}_e \to \bar{t} + b$

(l) $\Lambda + p \to K^- + p + p$

(m) $p + \bar{p} \to \pi^+ + \pi^- + \pi^0$

(n) $\mu^- \to e^+ + e^- + e^- + \nu_e + \nu_\mu$

(o) $\mu^+ + \tau^- \to \gamma + \gamma + \gamma$

(p) $J/\psi \to \nu_\tau + \bar{\nu}_\tau$

2 Nuclear Masses (16 Points)

Consider the Bethe-Weizsäcker semi-emperical mass formula (SEMF) and the isotope table (see Appendices).

(a) Briefly explain each of the terms in the SEMF. Comment on the A, N and Z dependence. (3 points).

(b) Give the expression for the binding energy per nucleon. Use the result to argue why the most strongly bound isotopes generally have $N > Z$. *Hint*: write the binding energy as a function of Z for fixed A and show that the maximum has $Z < A/2$. You may use $\delta = 0$. (5 points)

(c) If $^{219}_{88}$Ra would decay via α, β^- or β^+-emission, what would in each case be the daughter nucleus? (3 points)

(d) Which of the three decay modes in (c) are allowed? Why (not)? Which of the allowed decay modes will dominate (motivate)? *Note*: take m_α from the appendix and use $m_{e^\pm} = 0$. (5 points)

3 Descriptions (16 Points)

Explain what is meant by the following terms (in relation to subatomic physics). Be specific! (2 points each):

(a) weak interaction
(b) cross section
(c) form factor
(d) hadron
(e) Cabbibo angle
(f) coupling constant
(g) isotope
(h) color

4 Mass Measurement (10 Points)

The mass of fundamental particles can be measured using several methods. Three of them are: magnetic spectrometer, Penning trap and kinematic analysis.

(a) For each method explain why it is sensitive to the mass of a particle. (5 points)

(b) Which method is preferred to measure the mass of :

I. proton

II. neutron

III. muon ($\tau = 2.2\,\mu$s)

IV. tau ($\tau = 291\,$fs)

Motivate your choice. (5 points)

5 Decay Rate and Branching Ratio (16 Points)

Natural Lanthanum has an atomic weight of 138.91 and contains 0.09% of the isotope $^{138}_{57}$La. This has two decay modes: $^{138}_{57}\text{La} \rightarrow^{138}_{58} \text{Ce}+e^{-}+\bar{\nu}_e$ (beta-decay) and $^{138}_{57}\text{La}+e^{-} \rightarrow^{138}_{56} \text{Ba}^{*} + \nu_e$ (electron capture), followed by the electromagnetic decay of the excited state $^{138}_{56}\text{Ba}^{*} \rightarrow^{138}_{56} \text{Ba} + \gamma$ (radiative decay). There are 7.8×10^{2} β particles emitted per second per kilogram of natural lanthanum and there are 50 photons emitted per 100 β^{-} particles. Estimate the mean lifetime of $^{138}_{57}$La.

6 Parity Violation in a Scattering Reaction (16 Points)

Consider the reaction $e^+ + e^- \to \mu^+ + \mu^-$.

(a) What is the dominant mechanism for this reaction. Draw its lowest order Feynman Diagram (2 points).

The differential cross-section is given by

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{(\alpha\hbar c)^2}{4E_{CM}^2}(1 + \cos^2\theta),$$

where E_{CM} is the center-of-mass energy and θ the angle between the outgoing muons and incoming electrons.

(b) Give the expression for the total cross-section (4 points).

The weak interaction also contributes to this process. In fact, it adds to above differential cross-section a term of the form

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Weak}} = \frac{(\alpha\hbar c)^2}{4E_{CM}^2} C_{\text{Weak}} \cos\theta,$$

where C_{Weak} is a constant.

(c) Show that $C_{\text{Weak}} \neq 0$ implies parity violation (3 points).

The total differential cross section becomes:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Total}} = \left(\frac{d\sigma}{d\Omega}\right) + \left(\frac{d\sigma}{d\Omega}\right)_{\text{Weak}}. \tag{1}$$

We can measure C_{Weak} by looking at the 'forward-backward' asymmetry

$$A_{fb} = \frac{\sigma_f - \sigma_b}{\sigma_f + \sigma_b}, \tag{2}$$

where σ_f (σ_b) is the total cross section in the forward (backward) direction defined by $0 \leq \cos\theta \leq 1$ ($-1 \leq \cos\theta \leq 0$).

(d) Derive a relation between C_{Weak} and A_{fb} (5 points).

(e) Can we learn something about C_{Weak} by measuring the total cross-section $\sigma = \sigma_f + \sigma_b$? Explain. (2 points)

Constants

Speed of light	c	$2.998 \cdot 10^{8}$	m/s
Planck constant	h	$4.136 \cdot 10^{-24}$	GeV·s
	$\hbar = \frac{h}{2\pi}$	$6.582 \cdot 10^{-25}$	GeV/c
Electron charge	e	$1.602 \cdot 10^{-19}$	C
Electron mass	m_e	0.510998918(44)	MeV/c^2
Proton mass	m_p	938.272029(80)	MeV/c^2
Neutron mass	m_n	939.565360(81)	MeV/c^2
Deuteron mass	m_d	1875.61282(16)	MeV/c^2
Alpha particle mass	m_α	3727.37917(32)	MeV/c^2
Electron neutrino mass	m_{ν_e}	< 2.2	eV/c^2
Muon mass	m_μ	105.658369(9)	MeV/c^2
Tau mass	m_τ	1776.84(17)	MeV/c^2
Charged pion mass	$m_{\pi^\pm}$	139.57018(35)	MeV/c^2
Neutral pion mass	m_{π^0}	134.9766(6)	MeV/c^2
$W^\pm$-boson mass	m_W	80.403(29)	MeV/c^2
Z^0-boson mass	m_W	91.1876(21)	MeV/c^2
Avogadro's number	N_A	$6.02214179(30) \cdot 10^{23}$	mol^{-1}

Semi-Emperical Mass Formula (Bethe-Weizsäcker)

$$M(A,Z) = Nm_n + Zm_p - a_v A + a_s A^{2/3} + a_c \frac{Z^2}{A^{1/3}} + a_a \frac{(A-2Z)^2}{4A} + \frac{\delta}{A^{1/2}}$$

$$\begin{aligned} a_v &= 15.67 \ \mathrm{MeV}/c^2 \\ a_s &= 17.23 \ \mathrm{MeV}/c^2 \\ a_c &= 0.714 \ \mathrm{MeV}/c^2 \\ a_a &= 93.15 \ \mathrm{MeV}/c^2 \\ \delta &= 0 \ \text{odd } A \\ &= -11.2 \ \mathrm{MeV}/c^2, \quad Z \text{ and } N \text{ even} \\ &= +11.2 \ \mathrm{MeV}/c^2, \quad Z \text{ and } N \text{ odd} \end{aligned}$$

Conversion Factors

Electronvolt	eV	$1.60217653(14) \cdot 10^{-19}$	J
Tesla	T	$0.561 \cdot 1030$	MeV/c^2·C·s
kilogram	kg	$5.60958896(48) \cdot 10^{35}$	eV/c^2
barn	b	$1 \cdot 10^{-28}$	m^2

Note: For some of the questions different approaches are possible, such that you may not necessarily need all of the given constants and equations. Unless specifically stated, the final results are sufficient if given to 2 significant figures (2 leading digits).

Isotope Table near $^{219}_{88}$Ra

Z			217U	218U	219U	220U	221U	222U	223U	224U	225U	226U	227U	228U	229U	230U	231U
	214Pa	215Pa	216Pa	217Pa	218Pa	219Pa	220Pa	221Pa	222Pa	223Pa	224Pa	225Pa	226Pa	227Pa	228Pa	229Pa	230Pa
90	213Th	214Th	215Th	216Th	217Th	218Th	219Th	220Th	221Th	222Th	223Th	224Th	225Th	226Th	227Th	228Th	229Th
	212Ac	213Ac	214Ac	215Ac	216Ac	217Ac	218Ac	219Ac	220Ac	221Ac	222Ac	223Ac	224Ac	225Ac	226Ac	227Ac	228Ac
88	211Ra	212Ra	213Ra	214Ra	215Ra	216Ra	217Ra	218Ra	219Ra	220Ra	221Ra	222Ra	223Ra	224Ra	225Ra	226Ra	227Ra
	210Fr	211Fr	212Fr	213Fr	214Fr	215Fr	216Fr	217Fr	218Fr	219Fr	220Fr	221Fr	222Fr	223Fr	224Fr	225Fr	226Fr
86	209Rn	210Rn	211Rn	212Rn	213Rn	214Rn	215Rn	216Rn	217Rn	218Rn	219Rn	220Rn	221Rn	222Rn	223Rn	224Rn	225Rn
	208At	209At	210At	211At	212At	213At	214At	215At	216At	217At	218At	219At	220At	221At	222At	223At	
84	207Po	208Po	209Po	210Po	211Po	212Po	213Po	214Po	215Po	216Po	217Po	218Po	219Po	220Po			
	123		125		127		129		131		133		135		137		N

E.2.4 Low-Lying Baryons

Particle	I, J^P	Mass (MeV/c^2)	Mean lifetime or width	Decay Mode	Decay Fraction (%)
Unflavoured states of light quarks ($S = C = \tilde{B} = 0$) Quark content: $N = (p, n) : p = uud,\ n = udd;\ \Delta^{++} = uuu,\ \Delta^{+} = uud,\ \Delta^{0} = udd,\ \Delta^{-} = ddd$					
p	$\frac{1}{2}, \frac{1}{2}^+$	938.27203(±8)	>2.1 × 10^{29} yr		
n	$\frac{1}{2}, \frac{1}{2}^+$	939.56536(±8)	8.857(±8) × 10^2 s	$pe^-\bar{\nu}_e$	100
Δ	$\frac{3}{2}, \frac{3}{2}^+$	1232(±1)	118(±2) MeV	$N\pi$	100
Strange baryons ($S = -1,\ C = \tilde{B} = 0$) Quark content: $\Lambda = uds;\ \Sigma^+ = uus,\ \Sigma^0 = uds,\ \Sigma^- = dds,$ similarly for Σ^*s.					
Λ	$0, \frac{1}{2}^+$	1115.683(±6)	2.631(±20) × 10^{-10}	$p\pi^-$	63.9(±5)
				$n\pi^0$	35.8(±5)
Σ^+	$1, \frac{1}{2}^+$	1189.37(±7)	8.018(±26) × 10^{-11}	$p\pi^0$	51.57(±30)
				$n\pi^+$	48.31(±30)
Σ^0	$1, \frac{1}{2}^+$	1192.642(±24)	7.4(±7) × 10^{-20}	$\Lambda\gamma$	100
Σ^-	$1, \frac{1}{2}^+$	1197.449(±30)	1.479(±11) × 10^{-10}	$n\pi^-$	99.848(±5)
Σ^{*+}	$1, \frac{3}{2}^+$	1382.8(±4)	35.8(±8) MeV	$\Lambda\pi$	87.0(±15)
				$\Sigma\pi$	11.7(±15)
Σ^{*0}	$1, \frac{3}{2}^+$	1383.7(±10)	36(±5) MeV	as above	
Σ^{*-}	$1, \frac{3}{2}^+$	1387.2(±5)	39.4(±21) MeV	as above	
Strange baryons ($S = -2,\ C = \tilde{B} = 0$) Quark content: $\Xi^0 = uss,\ \Xi^- = dss,$ similarly for Ξ^*s					
Ξ^0	$\frac{1}{2}, \frac{1}{2}^+$	1314.86(±20)	2.90(±9) × 10^{-10} s	$\Lambda\pi^0$	99.525(±12)
Ξ^-	$\frac{1}{2}, \frac{1}{2}^+$	1321.71(±7)	1.639(±15) × 10^{-10} s	$\Lambda\pi^-$	99.887(±35)
Ξ^{*0}	$\frac{1}{2}, \frac{3}{2}^+$	1531.80(±32)	9.1(±5) MeV	$\Lambda\bar{K},\ \Sigma\bar{K},\ \Xi\pi$	seen
Ξ^{*-}	$\frac{1}{2}, \frac{3}{2}^+$	1535.0(±6)	9.9(±18) MeV	as above	
Strange baryons ($S = -3,\ C = \tilde{B} = 0$) Quark content: $\Omega^- = sss$					
Ω^-	$0, \frac{3}{2}^+$	1672.45(±29)	8.21(±11) × 10^{-11} s	ΛK^-	67.8(±7)
				$\Xi^0\pi^-$	23.6(±7)
				$\Xi^-\pi^0$	8.6(±4)

Particle	I, J^P	Mass (MeV/c^2)	Mean lifetime or width	Decay Mode	Decay Fraction (%)
Charmed baryons ($S = 0,\ C = +1,\ \tilde{B} = 0$) Quark content: $\Lambda_c^+ = udc$; $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$, similarly for $\Sigma_c^* s$					
Λ_c^+	$0, \frac{1}{2}^+$	2286.46(±14)	$2.00(\pm 6) \times 10^{-13}$ s	$n + X$	50(±16)
				$p + X$	50(±16)
				$\Lambda + X$	35(±11)
				$\Sigma^\pm + X$	10(±5)
				$e^+ + X$	4.5(±17)
Σ_c^{++}	$1, \frac{1}{2}^+$	2454.02(±18)	2.23(±30) MeV	$\Lambda_c^+ \pi^+$	seen
Σ_c^+	$1, \frac{1}{2}^+$	2452.9(±4)	<4.6 MeV		
Σ_c^0	$1, \frac{1}{2}^+$	2453.76(±18)	2.2(±4) MeV		
Σ_c^{*++}	$1, \frac{3}{2}^+$	2518.4(±6)	14.9(±19) MeV	$\Lambda_c^+ \pi^+$	seen
Σ_c^{*+}	$1, \frac{3}{2}^+$	2517.5(±23)	<1.7 MeV		
Σ_c^{*0}	$1, \frac{3}{2}^+$	2518.0(±5)	16.1(±21) MeV		
Charmed strange baryons ($S = -1, -2,\ C = +1,\ \tilde{B} = 0$) Quark content: $\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, similarly for $\Xi_c^* s$; $\Omega_c^0 = ssc$					
Ξ_c^+	$\frac{1}{2}, \frac{1}{2}^+$	2467.9(±4)	$4.42(\pm 26) \times 10^{-13}$ s	several seen	
Ξ_c^0	$\frac{1}{2}, \frac{1}{2}^+$	2471.0(±4)	$1.12(\pm 4) \times 10^{-13}$ s	several seen	
Ω_c^0	$\frac{1}{2}, \frac{1}{2}^+$	2697.5(±26)	$6.9(\pm 1.2) \times 10^{-14}$ s	several seen	
Ξ_c^{*+}	$\frac{1}{2}, \frac{3}{2}^+$	2646.6(±14)	<3.1MeV	$\Xi_c^0 \pi^+$	seen
Ξ_c^{*0}	$\frac{1}{2}, \frac{3}{2}^+$	2646.1(±12)	<5.5MeV	$\Xi_c^+ \pi^-$	seen
Bottom baryons ($S = C = 0,\ \tilde{B} = -1$) Quark content: $\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$					
Λ_b^0	$0, \frac{1}{2}^+$	5620.2(±16)	$1.383(\pm 48) \times 10^{-12}$s	$\Lambda_c^+ + X$	9.1(±2.3)
$\Xi_b^{0,-}$	$\frac{1}{2}, \frac{1}{2}^+$	5792.4(±3)	$1.42(\pm 35) \times 10^{-12}$ s		

E.2.5 Low-Lying Mesons

In the J^{PC} column, the C quantum number applies to just the neutral states of an isospin multiplet.

Particle	I, J^{PC}	Mass (MeV/c^2)	Mean lifetime or width	Decay Mode	Decay Fraction (%)
Unflavoured states of light quarks ($S = C = \tilde{B} = 0$) Quark content: $I = 1$ states, $u\bar{d}$, $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$, $d\bar{u}$; $I = 0$ states, $c_1(u\bar{u} - d\bar{d}) + c_2 s\bar{s}$ ($c_{1,2}$ are constants)					
$\pi^\pm$	$1, 0^-$	139.57018(±35)	$2.6033(\pm 5) \times 10^{-8}$ s	$\pi^+\nu_\mu$	99.98770(±4)
π^0	$1, 0^{-+}$	134.9766(±6)	$8.4(\pm 6) \times 10^{-17}$ s	$\gamma\gamma$	98.798(±32)
η	$0, 0^{-+}$	547.853(±24)	1.30(±7) keV	$\gamma\gamma$	39.31(±20)
				$\pi^0\pi^0\pi^0$	32.56(±23)
				$\pi^+\pi^-\pi^0$	22.73(±28)
				$\pi^+\pi^-\gamma$	4.60(±6)
ρ	$1, 1^{--}$	775.49(±34)	149.4(±10) MeV	$\pi\pi$	~100
ω^0	$0, 1^{--}$	782.65(±12)	8.49(±9) MeV	$\pi^+\pi^-\pi^0$	89.2(±7)
				$\pi^0\gamma$	8.92(±24)
η'	$0, 0^{-+}$	957.66(±24)	0.205(±5) MeV	$\pi^+\pi^-\eta$	44.6(±14)
				$\pi^+\pi^-\gamma$	29.4(±9)
				$\pi^0\pi^0\eta$	20.7(±12)
				$\omega\gamma$	3.02(±31)
ϕ	$0, 1^{--}$	1019.455(±20)	4.26(±6) MeV	K^+K^-	49.2(±6)
				$K_L^0K_S^0$	34.0(±5)
				$\rho\pi + \pi^+\pi^-\pi^0$	15.25(±35)
Strange mesons ($S = \pm 1,\ C = \tilde{B} = 0$) Quark content: $K^+ = u\bar{s},\ K^0 = d\bar{s},\ \bar{K}^0 = s\bar{d},\ K^- = s\bar{u}$, similarly for K^*s					
$K^\pm$	$\frac{1}{2}, 0^-$	493.667(±16)	$1.2380(\pm 21) \times 10^{-8}$ s	$\mu^+\nu_\mu$	63.54(±14)
				$\pi^+\pi^0$	20.68(±13)
				$\pi^+\pi^+\pi^-$	5.59(±4)
				$\pi^0e^+\nu_e$	5.08(±5)
				$\pi^0\mu^+\nu_\mu$	3.35(±7)
$K^0, \bar{K}^0$	$\frac{1}{2}, 0^-$	497.614(±24)			
K_S^0	see note a		$8.953(\pm 5) \times 10^{-11}$ s	$\pi^+\pi^-$	69.20(±5)
				$\pi^0\pi^0$	30.69(±5)
K_L^0	see note a		$5.114(\pm 21) \times 10^{-8}$ s	$\pi^\pm e^\mp\nu_e(\bar{\nu}_e)$	40.55(±12)
				$\pi^\pm\mu^\mp\nu_\mu(\bar{\nu}_\mu)$	27.04(±7)
				$\pi^0\pi^0\pi^0$	19.52(±12)
				$\pi^+\pi^-\pi^0$	12.54(±5)
$K^{*\pm}$	$\frac{1}{2}, 1^-$	891.66(±26)	50.8(±9) MeV	$K\pi$	~100
K^{*0}	$\frac{1}{2}, 1^-$	896.00(±25)	50.3(±6) MeV	$K\pi$	~100

Particle	I, J^{PC}	Mass (MeV/c^2)	Mean lifetime or width	Decay Mode	Decay Fraction (%)
Charmed mesons ($S = 0,\ C = \pm1,\ \tilde{B} = 0$) Quark content: $D^+ = c\bar{d},\ D^0 = c\bar{u},\ \bar{D}^0 = u\bar{c},\ D^- = d\bar{c}$, similarly for D^*s					
$D^\pm$	$\frac{1}{2}, 0^-$	1869.12(±20)	$1.040(\pm7) \times 10^{-12}$ s	$K^0 + X$	
				plus	
				$\bar{K}^0 + X$	61(±5)
				$K^- + X$	25.7(±14)
				$\bar{K}^{*0} + X$	23(±5)
				$e^+ + X$	16.0(±4)
				$K^+ + X$	5.9(±8)
$D^0, \bar{D}^0$	$\frac{1}{2}, 0^-$	1864.84(±17)	$4.101(\pm15) \times 10^{-13}$ s	$K^- + X$	54.9(±28)
				$K^0 + X$	
				plus	
				$\bar{K}^0 + X$	47(±4)
				$\bar{K}^{*0} + X$	9(±4)
				$e^+ + X$	6.53(±17)
				$K^+ + X$	3.4(±4)
$D^{*\pm}$	$\frac{1}{2}, 1^-$	2010.27(±17)	96(±22) keV	$D^0\pi^+$	67.7(±5)
				$D^+\pi^0$	30.7(±5)
$D^{*0}, \bar{D}^{*0}$	$\frac{1}{2}, 1^-$	2006.97(±19)	<2.1 MeV	$D^0\pi^0$	61.9(±29)
				$D^0\gamma$	38.1(±29)
Charmed strange mesons ($S = \ C = \pm1,\ \tilde{B} = 0$) Quark content: $D_s^+ = c\bar{s},\ D_s^- = s\bar{c}$, similarly for D_s^*s					
$D_s^\pm$	$0, 0^-$	1968.49(±34)	$5.00(\pm7) \times 10^{-13}$ s	$K^0 + X$	
				plus	
				$\bar{K}^0 + X$	39(±28)
				$K^+ + X$	20(±16)
				$\phi + X$	18(±13)
				$K^- + X$	13(±13)
				$e^+ + X$	8(±7)
				$\tau^+\nu_\tau$	6.4(±15)
$D_s^{*\pm}$	$0, 1^-$	2112.3(±5)	<1.9 MeV	$D_s^+\gamma$	94.2(±7)
				$D_s^+\pi^0$	5.8(±7)
Bottom mesons ($S = C = 0,\ \tilde{B} = \pm1$) Quark content: $B^+ = u\bar{b},\ B^0 = d\bar{b},\ \bar{B}^0 = b\bar{d},\ B^- = b\bar{u}$, similarly for B^*s					
$B^\pm$	$\frac{1}{2}, 0^-$	5279.15(±31)	$1.638(\pm11) \times 10^{-12}$ s	$\bar{c}X$ (see note b)	97(±4)
				cX (see note b)	23.4(±20)
				$\ell^+\nu_\ell + X$	10.99(±28)
$B^0, \bar{B}^0$	$\frac{1}{2}, 0^-$	5279.53(±33)	$1.530(\pm9) \times 10^{-12}$ s	$\bar{c}X$ (see note b)	95(±5)
				cX (see note b)	24.6(±3)
				$\ell^+\nu_\ell + X$	10.33(±28)

Particle	I, J^{PC}	Mass (MeV/c^2)	Mean lifetime or width	Mode	Fraction (%)
Bottom strange mesons ($S = \mp 1,\ C = 0,\ \tilde{B} = \pm 1$) Quark content: $B_s^0 = s\bar{b},\ \bar{B}_s^0 = b\bar{s}$					
$B_s^0, \bar{B}_s^0$	0, 0$^-$	5366.3(±6)	1.470(±26) × 10^{-12} s	$D_s^- + X$	93(±25)
				$D_s^- \ell^+ \nu_\ell + X$	7.9(±24)
Bottom charmed mesons ($S = 0,\ \tilde{B} = C = \pm 1$) Quark content: $B_c^+ = c\bar{b},\ B_c^- = b\bar{c}$					
$B_c^\pm$	0, 0$^-$	6276(±4)	4.6(±17) × 10^{-13} s	several seen	
$c\bar{c}$ mesons					
$\eta_c(1S)$	0, 0^{-+}	2980.3(±12)	26.7(±30) MeV	$K\bar{K}\pi$	7.2(±12)
				$\eta\pi\pi$	4.9(±18)
				$\eta'\pi\pi$	4.1(±17)
$J/\psi(1S)$	0, 1^{--}	3096.916(11)	93.2(±21) keV	hadrons	87.7(±5)
				e^+e^-	5.94(±6)
				$\mu^+\mu^-$	5.93(±6)
$b\bar{b}$ mesons					
$\eta_b(1S)$	0, 0^{-+}	9388.9(±28)	?		
$\Upsilon(1S)$	0, 1^{--}	9460.30(±26)	54.02(±125) keV	$\eta' + X$	2.94(±24)
				$\ell^+\ell^-$ all ℓ	7.46(±36)

[a] These states are discussed in Section 6.6.1.

[b] $\bar{c}$ stands for any state containing a $\bar{c}$ quark and c stands for any state containing a c quark.