Kursanalys - KTH

Formulär för kursansvarig.
Kursanalysen utförs under kursens gång.
Nomenklatur: F – föreläsning, Ö – övning, R – räknestuga, L – laboration, S – seminarium)

KURSDATA Obligatorisk del

Kursens namn	**Kursnummer**
Relativistisk kvantfysik	SI2390
Kurspoäng och poäng fördelat på exam-former	**När kursen genomfördes**
7,5 hp (INL1, 4,5 hp och TEN1, 3 hp)	Läsåret 2021/2022 (period 3)
Kursansvarig och övriga lärare	**Undervisningstimmar, fördelat på F, Ö, R, L, S**
Professor Tommy Ohlsson Professor Tommy Ohlsson	18 x 2h F 3 x 2h S

Antal registrerade studenter	23
Prestationsgrad efter 1:a examenstillfället, i %	87,8
Examinationsgrad efter 1:a examenstillfället, i %	82,6

MÅL

Ange övergripande målen för kursen

Efter fullgjord kurs skall du kunna:
- tillämpa Poincarégruppen samt klassificera partikelrepresentationer.
- analysera Klein–Gordon- och Diracekvationerna.
- lösa Weylekvationen.
- känna till Maxwells ekvationer och klassisk Yang–Mills-teori.
- kvantisera Klein–Gordon-, Dirac- och Majoranafält samt ställa upp Lagrangetätheter för dessa fält.
- använda störningsteori inom enkla kvantfältteorier.
- ställa upp Lagrangetätheten för kvantelektrodynamik samt analysera denna.
- härleda Feynmanregler utifrån enkla kvantfältteorier samt tolka Feynmandiagram.
- analysera elementära processer i kvantelektrodynamik.
- beräkna strålningskorrektioner för elementära processer i kvantelektrodynamik.

Ange hur kursen är utformad för att uppfylla målen

Kursen är utformad så att föreläsningar och egna självstudier ska leda till att studenterna kan lösa skriftliga inlämningsuppgifter samt svara på teorifrågor och därmed uppfylla målen för kursen.

Eventuellt deltagande i länkmöte före kursstart

Synpunkter från detta

-

Kursens pedagogiska utveckling I

Beskriv de förändringar som gjorts sedan förra kursomgången. (Berätta även för studenterna vid kursstart)

Seminarier (3 x 2h) har införts i kursen. Meningen med seminarierna är att de ska vara studentaktiva.

Kontakt med studenterna under kursens gång

Studenter i årets kurs-nämnd:	Namn	E-post (lämnas blank vid webbpublicering)

Resultat av formativ mittkursenkät

Resultat av kursmöten

Kontakt med övriga lärare under kursens gång

Kommentarer

-

Kursenkät; teknologernas synpunkter Obligatorisk del

Att komma ihåg:
1) Uppmana, mha kursnämnden, till ifyllande av kursenkät i anslutning till / just efter slutexaminationen
2) Delge kursnämnden enkäten
3) Publicera enkäten under en kortare tid

Period, då enkäten var aktiv	2022-03-15 – 2022-03-25
Frågor, som adderades till standardfrågorna	• What is your overall impression of the course? • How would you rate the difficulty of the course? • Has there been much overlap with other courses? • How were the quizzes? • How were the (hand-in) homework problems? • How was the oral examination? • What is your opinion about the course description and the administration of the course? • What is your opinion about the course literature? • How were the lectures? • How were the seminars? • Please enter any further comments on the course below.
Svarsfrekvens	82 %
Förändringar sedan förra genomförandet	Seminarier (3 x 2h) har införts i kursen. Meningen med seminarierna är att de ska vara studentaktiva.
Helhetsintryck	Enligt kursenkäten svarade majoriteten av studenterna att de var mycket eller ganska nöjda med kursen i sin helhet.
Relevanta webb-länkar	-

Kursansvarigs tolkning av enkät

Positiva synpunkter	Se bilaga.
Negativa synpunkter	Se bilaga.
Var kursen relevant i förhållande till kursmålen?	-
Syn på förkunskaperna	-
Syn på undervisningsformen	Föreläsningarna ansågs vara mycket bra eller bra av en majoritet av studenterna. Seminarierna ansågs vara bra eller medelgoda av en majoritet av studenterna. Jag tycker att studenterna i allmänhet borde vara mer aktiva under seminarierna. Studenter som har sin bakgrund från andra universitet än KTH är normalt sett mer aktiva vid seminarier än de som har sin bakgrund från KTH.
Syn på kurslitt/ kursmaterial	Kurslitteraturen ansågs vara bra eller medelbra av en majortitet av studenterna.
Syn på examinationen	Inlämningsuppgifterna ansågs vara svåra av en majoritet av studenterna, medan de muntliga tentamina och de s.k. quizzes ansågs vara medelsvåra.
Speciellt intressanta kommentarer	Se bilaga.

Synpunkter från övriga lärare efter avslutad kurs

Vad fungerade bra	-
Vad fungerade mindre bra	-

Resultat av kursnämndsmöte efter examination

Studenternas sammanfattn.	-
Förslag till förändringar	-
Länk till kursnämndsprot.	-

Kursansvarigs sammanfattande berättelse

Helhetsintryck	Jag är i stort sett mycket nöjd med utfallet av kursen. Studenterna hade, som tidigare år, liknande förkunskaper. Antalet studenter var något färre än jämfört med föregående år.
Positiva synpunkter	Se bilaga med resultat av kursenkät.
Negativa synpunkter	Se bilaga med resultat av kursenkät.
Syn på förkunskaperna	-
Syn på undervisningsformen	-
Syn på kurslitt/ kursmaterial	Läroboken, som har använts tio gånger tidigare, fungerar bra att använda som kurslitteratur i kursen, vilken är Tommy Ohlsson, Relativistic Quantum Physics (Cambridge University Press, 2011).
Syn på examinationen	Jag är på det stora hela nöjd med hur examinationen har fungerat och har inga större planer på att förändra den tills nästa kursomgång.

Kursens pedagogiska utveckling II Obligatorisk del

Hur förändringarna till denna kursomgång fungerade	Jag tycker att studenterna i allmänhet borde vara mer aktiva under seminarierna. Seminarierna kommer förslagsvis att användas under nästa kursomgång också.
Förändringar som bör göras inför nästa kursomgång	Jag tycker att det vore bättre att kursen skulle ges under två perioder istället för en period, eftersom det ger studenterna mer tid att ”smälta” kursmaterialet som uppfattas som svårt i allmänhet av studenterna.

Övrigt

Kommentarer

Bilagor:

1. Kurs-PM: SI2390 Relativistic Quantum Physics, 7.5 ECTS credits
2. Obligatoriska inlämningsuppgifter [Homework Problems #1-#3 in SI2390 Relativistic Quantum Physics, 7.5 credits – Spring 2022, Periods 3]
3. Resultat av: Relativistic Quantum Physics, SI2390, vt 2022

Instruktioner till kursanalysformulär

1) Kursanalysformuläret fylls i interaktivt; fälten expanderar automatiskt.
2) Fyll i fälten inom en månad efter kursens slut. (Viktigt krav från KTH!)
Skicka sedan till studierektor (som vidarebefordrar till prefekt och programansvarig).
3) Försök att ge så kompletta uppgifter som möjligt.
Tänk på att kursanalysen är ett hjälpmedel inte bara för teknologerna, utan även för Dig som lärare.
4) Med ”prestationsgrad” avses antalet presterade poäng hittills på kursen (inlämningsuppgifter, projektuppgifter, laborationer etc.) dividerat med antalet möjliga poäng för de registrerade studenterna.
Med ”examinationsgrad” avses antalet studenter av de registrerade, som klarat samtliga kurskrav.
Kurssekreteraren hjälper gärna till här.
5) Kontakten med studenterna:

- Etablera kursnämnd under kursens första vecka (minst två studerande, gärna genusbalanserad).
- Lämplig bonus till kursnämndsdeltagarna är fri kurslitteratur.
- Om kursnämnd ej kan etableras, skall sektionens studienämndsordförande (SNO) kontaktas genast (se www.ths.kth.se/utbildning/utbildningsradet.html för kontaktuppgifter).
- Kursnämnden skall sammanträda under kursens gång, exempelvis i halvtid. Har mittkursutvärdering genomförts, skall den diskuteras då.
- Kursnämnden skall även ha ett möte efter det att studenterna har besvarat kursutvärderingen och kursnämndens studenter fått tillgång till resultaten. Undantaget är kurser i period fyra, där mötet bör ske direkt efter examinatioinen är avslutad för att analysen skall vara klar innan sommaren.
- Under det avslutande kursnämndsmötet bör studenterna föra protokoll. Detta protokoll skall kursansvarig få senast en vecka efter mötet.
- Det är kursansvarigs ansvar att kalla till kursnämndsmöten.

Slutligen, tänk på:

- det är viktigt att kursanalysen tydligt *visar utvecklingen av kursens kvalitet* från ett läsår till nästa.
- möjligheten att lägga ut kursanalysen på kurshemsidan.
- spara kursanalysen till förberedelsearbetet inför nästa kursomgång.

Department of Physics

SI2390 Relativistic Quantum Physics
7.5 credits
Spring 2022, Period 3

General Information

"Relativistic Quantum Physics" is a course where important theories for elementary particle physics and symmetries are learned. During the course, it will be illustrated how relativistic symmetries and gauge symmetries can restrict "possible" theories. The course will give an introduction to perturbation theory and Feynman diagrams. The problem with divergencies will be mentioned and the concepts for regularization and renormalization will be illustrated.

The course is recommended to (and elective for) students in the first year of the Master's Programme in Engineering Physics (*i.e.*, the fourth year of the Degree Programme in Engineering Physics) at KTH specializing in physics in general and in theoretical physics in particular as well as to PhD students in physics and theoretical physics. The language of the course is English.

Intended Learning Outcomes

After completion of the course you should be able to:

- apply the Poincaré group as well as classify particle representations.
- analyze the Klein–Gordon and the Dirac equations.
- solve the Weyl equation.
- know Maxwell's equations and classical Yang–Mills theory.
- quantize Klein–Gordon, Dirac, and Majorana fields as well as formulate the Lagrangian for these fields.
- use perturbation theory in simple quantum field theories.
- formulate the Lagrangian for quantum electrodynamics as well as analyze this.

- derive Feynman rules from simple quantum field theories as well as interpret Feynman diagrams.
- analyze elementary processes in quantum electrodynamics.
- compute radiative corrections to elementary processes in quantum electrodynamics.

Syllabus

The course consists of two parts:

Part I. Relativistic quantum mechanics: Tensor notation. The Lorentz and Poincaré groups. Casimir operators. Irreducible representations of particles. The Klein–Gordon equation. The Dirac equation. The structure of Dirac particles. The Dirac equation: central potentials. The Weyl equation.

Part II. Introduction to relativistic quantum field theory: Neutral and charged Klein–Gordon fields. The Dirac field. The Majorana field. Maxwell's equations and quantization of the electromagnetic field. Introduction to Yang–Mills theory. Asymptotic fields: LSZ formulation. Perturbation theory. Introduction to quantum electrodynamics. Interacting fields and Feynman diagrams. Elementary processes of quantum electrodynamics. Introduction to regularization, renormalization, and radiative corrections.

Prerequisites

The following courses are mandatory:

- Quantum Physics
- Special Relativity Theory

The following course is recommended:

- Classical Theoretical Physics

Lectures and Lecturer

The course contains 36 h lectures (18×2 h), which will be given in English. The lecturer, course responsible, and examiner of the course is:

Professor Tommy Ohlsson
Department of Physics, KTH Royal Institute of Technology
Visiting address: Roslagstullsbacken 21, floor 5, room A5:1029
Telephone: 08-7908261
E-mail: tohlsson@kth.se

Course Literature

The course literature consists of one book (mainly):

- T. Ohlsson, *Relativistic Quantum Physics – From Advanced Quantum Mechanics to Introductory Quantum Field Theory*, Cambridge (2011)

Further recommended reading:

- A.Z. Capri, *Relativistic Quantum Mechanics and Introduction to Quantum Field Theory*, World Scientific (2002)
- W. Greiner, *Relativistic Quantum Mechanics – Wave Equations*, Springer (2000)
- F. Gross, *Relativistic Quantum Mechanics and Field Theory*, Wiley (1993)
- F. Mandl and G. Shaw, *Quantum Field Theory*, rev. ed., Wiley (1994)
- J. Mickelsson, T. Ohlsson, and H. Snellman, *Relativity Theory*, KTH (2005)
- M.E. Peskin and D.V. Schroeder, *Introduction to Quantum Field Theory*, Harper-Collins (1995)
- F. Schwabl, *Advanced Quantum Mechanics*, Springer (1999)
- S.S. Schweber, *An Introduction to Relativistic Quantum Field Theory*, Dover (2005)
- F.J. Ynduráin, *Relativistic Quantum Mechanics and Introduction to Field Theory*, Springer (1996)

Requirements

Hand in assignments (INL1; 4.5 ECTS credits) and an oral exam (TEN1; 3 ECTS credits).

Examination

The examination of the course will be a combination of homework problems (INL1) and an oral examination (TEN1).

INL1. There will be three sets of homework problems, which each consists of two parts, during the course. These will be distributed and should be handed in according to the following scheme:

Homework Problems	Out	In
Set # 1 – Part I	Lecture 5 (January 26, 2022)	February 2, 2022 @ 16:00–17:00
Set # 1 – Part II	Lecture 5 (January 26, 2022)	February 9, 2022 @ 18:00
Set # 2 – Part I	Lecture 11 (February 9, 2022)	February 16, 2022 @ 16:00–17:00
Set # 2 – Part II	Lecture 11 (February 9, 2022)	February 23, 2022 @ 16:00
Set # 3 – Part I	Lecture 17 (February 28, 2022)	March 7, 2022 @ 16:00–17:00
Set # 3 – Part II	Lecture 17 (February 28, 2022)	March 14, 2022 @ 16:00

TEN1. The oral examinations will take place after the last lecture of the course. Each examination will take approximately 15 minutes. The time for the examination will be agreed upon between the student and the examiner.

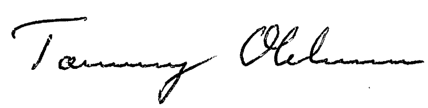
Grading

The different grades are: A, B, C, D, E, Fx, and F. The grades will be awarded according to the following scheme:

Grade	Homework Problems (INL1)	Oral Examination (TEN1)
F	$<$ 50 % of all problems correct	Failed
Fx	$<$ 50 % of all problems correct	Passed
Fx	$\geq$ 50 % of all problems correct	Failed
E	$\geq$ 50 % of all problems correct	Passed
D	$\geq$ 60 % of all problems correct	Passed
C	$\geq$ 70 % of all problems correct	Passed
B	$\geq$ 80 % of all problems correct	Passed
A	$\geq$ 90 % of all problems correct	Passed

In addition, you need to obtain at least 50 % on each homework problem set in order to obtain a passing grade (E or higher). If you obtain a total result of more than 50 %, but do not fulfill this criterion, you will be given the grade Fx and a chance to make a completing task for the grade E.

Good luck with the course!



Schedule and Program of Lectures

Schedule of Lectures

#	Week	Day	Date	Time	Room	Contents
1	3	Tuesday	January 18, 2022	10-12	FD41	Introduction
2		Wednesday	January 29, 2022	15-17	FD41	General description of relativistic states
3		Friday	January 21, 2022	10-12	FD41	The Klein–Gordon equation
4	4	Monday	January 24, 2022	10-12	FD41	The Dirac equation
5		Wednesday	January 26, 2022	10-12	FB51	—”—
S1		—”—	—”—	15-17	FD41	Seminar 1
6		Friday	January 28, 2022	10-12	FD41	The Dirac equation
7	5	Monday	January 31, 2022	10-12	FD41	Quantization of the non-relativistic string
8		Wednesday	February 2, 2022	10-12	FB55	Introduction to relativistic quantum field theory
9		Friday	February 4, 2022	10-12	FD41	Quantization of the Klein–Gordon field
10	6	Monday	February 7, 2022	10-12	FD41	Quantization of the Dirac field
11		Wednesday	February 9, 2022	10-12	FD41	Maxwell's equations and quantization of the electromagnetic field
S2		—”—	—”—	15-17	FD41	Seminar 2
12		Friday	February 11, 2022	10-12	FD41	Introduction to Yang–Mills theory
13	7	Wednesday	February 16, 2022	10-12	FD41	Asymptotic field and the LSZ formalism
14		Friday	February 18, 2022	10-12	FD41	Perturbation theory
15	8	Monday	February 21, 2022	10-12	FD41	—”—
16		Wednesday	February 23, 2022	10-12	FD41	—”—
S3		Friday	February 25, 2022	10-12	FD41	Seminar 3
17	9	Monday	February 28, 2022	10-12	FD41	Elementary processes of quantum electrodynamics
18		Friday	March 4, 2022	10-12	FB51	Introduction to regularization, renormalization, and radiative corrections

Program of Lectures

Below, RQP refers to the textbook T. Ohlsson, *Relativistic Quantum Physics – From Advanced Quantum Mechanics to Introductory Quantum Field Theory*, Cambridge (2011).

Lecture 0: Refresh chapter 1 in Mickelsson, Ohlsson & Snellman or some similar material on special relativity theory!

Lecture 1: Tensor notation. The Lorentz and Poincaré groups. Casimir operators. Irreducible representations of particles.
Literature: Chapter 1 in RQP.

Lecture 2: General description of relativistic one-particle states.
Literature: Chapter 1 in RQP.
For the interested student: E. Wigner, *On Unitary Representations of the Inhomogeneous Lorentz Group*, Ann. Math. **40**, 149 (1939).

Lecture 3: The Klein–Gordon equation. The Klein paradox.
Literature: Chapter 2 in RQP.

Lecture 4: The Dirac equation. Gamma "gymnastics".
Literature: Chapter 3 in RQP.

Lecture 5: The structure of Dirac particles. The Dirac equation: central potentials.
Literature: Chapter 3 in RQP.

Lecture 6: The hydrogenic atom. The Weyl equation.
Literature: Chapter 3 in RQP.

Lecture 7: Quantization of the non-relativistic string.
Literature: Chapter 4 in RQP.

Lecture 8: Introduction to relativistic quantum field theory.
Literature: Chapter 5 in RQP.

Lecture 9: Neutral and charged Klein–Gordon fields.
Literature: Chapter 6 in RQP.

Lecture 10: The Dirac field. The Majorana field.
Literature: Chapter 7 in RQP.

Lecture 11: Maxwell's equations and quantization of the electromagnetic field.
Literature: Chapter 8 in RQP.

Lecture 12: Introduction to Yang–Mills theory.
Literature: Chapter 9 in RQP.

Lecture 13: Asymptotic fields: LSZ (Lehmann–Symanzik–Zimmermann) formulation.
Literature: Chapter 10 in RQP.

Lecture 14: Perturbation theory.
Literature: Chapter 11 in RQP.

Lecture 15: see lecture 14.
Literature: Chapter 11 in RQP.

Lecture 16: Introduction to quantum electrodynamics. Interacting fields and Feynman diagrams.
Literature: Chapter 11 in RQP.

Lecture 17: Elementary processes of quantum electrodynamics.
Literature: Chapter 12 in RQP.

Lecture 18: Introduction to regularization, renormalization, and radiative corrections.
Literature: Chapter 13 in RQP.

Department of Physics

Homework Problems #1 in SI2390 Relativistic Quantum Physics, 7.5 credits Spring 2022, Period 3

Deadlines: Part I: Quiz on February 2, 2022 @ 16:00–17:00
Part II: February 9, 2022 @ 18:00

Examiner: Prof. Tommy Ohlsson
(Telephone: 08-790 8261 • E-mail: `tohlsson@kth.se`)

GOOD LUCK!

Part I

1. a) Compute $\mathrm{tr}(\gamma^\mu\gamma^\nu)$, $\mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^\rho)$, $\mathrm{tr}(\gamma^\mu\gamma^5)$, and $\mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^5)$.

   b) Compute $\gamma^\mu\gamma^\nu\gamma_\mu$, $\not{p}\gamma^\mu\not{p}$, $\gamma^\mu\gamma^5\gamma_\mu\gamma_5$, and $\gamma^\mu\gamma^\alpha\gamma^\beta\gamma_\mu$.

2. a) Determine the Hamiltonian $H = \beta m + \boldsymbol{\alpha}\cdot\mathbf{p}$ using the Dirac equation for a free particle $(\mathrm{i}\gamma^\mu\partial_\mu - m\mathbb{1}_4)\psi(x) = 0$.

   b) Does this Hamiltonian commute with any of the three operators $\mathbf{L} = \mathbf{x}\times\mathbf{p}$ (angular momentum), $\mathbf{S} = \boldsymbol{\Sigma}/2$ (spin), where $\boldsymbol{\Sigma} = \mathrm{i}\boldsymbol{\gamma}\times\boldsymbol{\gamma}/2$, and $\mathbf{J} = \mathbf{L}+\mathbf{S}$ (total angular momentum)?

Part II

1. Given the transformation law of the 4-momentum P under Lorentz transformations

$$U^{-1}(\Lambda,0)\,P^\mu\,U(\Lambda,0) = (\Lambda^{-1})^\mu{}_\nu\,P^\nu,$$

   show that $[M^{\rho\sigma}, P^\mu] = -\mathrm{i}(g^{\sigma\mu}P^\rho - g^{\rho\mu}P^\sigma)$.

   Hint: Use the infinitesimal Lorentz transformation $\Lambda^\mu{}_\nu = \delta^\mu_\nu + \omega^\mu{}_\nu$, where $\omega^{\mu\nu} = -\omega^{\nu\mu}$, and the infinitesimal version of the unitary operator that represents the element $(\Lambda,0)$ of the Poincaré group, i.e. $U(\Lambda,0) = \exp(-\frac{\mathrm{i}}{2}\omega_{\mu\nu}M^{\mu\nu})$.

2. *The Klein paradox for the Dirac equation.* Solve the Dirac equation for a step-function potential on the form

$$V(z) = \begin{cases} 0, & z<0 \\ V_0, & z>0 \end{cases},$$

   where V_0 is a positive constant. Evaluate the current reflected and transmitted.

Department of Physics

Homework Problems #2 in SI2390 Relativistic Quantum Physics, 7.5 credits Spring 2022, Period 3

Deadlines:	Part I: Quiz on February 16, 2022 @ 16:00–17:00
	Part II: February 23, 2022 @ 16:00
Examiner:	Prof. Tommy Ohlsson
	(Telephone: 08-790 8261 • E-mail: `tohlsson@kth.se`)

GOOD LUCK!

Part I

1. a) Suppose the field $\phi = \phi(t, z)$, where t is time and z describes a spatial direction, is a solution to the two-dimensional Klein–Gordon equation $(\Box_2 + m^2)\phi(t, z) = 0$, where $\Box_2 \equiv \partial_0^2 - \partial_z^2$, with periodic boundary conditions and expanded in normal modes as

$$\phi(t, z) = \sum_{n=-\infty}^{\infty} c_n \left[a_n \phi_n(t, z) + a_n^\dagger \phi_n^*(t, z)\right], \quad \pi(t, z) = \dot{\phi}(t, z),$$

where the operators a_n satisfy the commutation relations

$$[a_n, a_{n'}] = \left[a_n^\dagger, a_{n'}^\dagger\right] = 0, \quad \left[a_n, a_{n'}^\dagger\right] = \delta_{nn'},$$

the states $\phi_n(t, z) = \frac{1}{\sqrt{\ell}} \mathrm{e}^{i(k_n z - \omega_n t)}$ ($k_n = 2\pi n/\ell,\ n = 0, \pm 1, \pm 2, \ldots$ and $\omega_n > 0$), and

$$\int_0^\ell \phi_n^*(t, z)\phi_m(t, z)\,\mathrm{d}z = \delta_{nm}.$$

Find the coefficients c_n, which will ensure that the canonical commutation relations assume the standard form

$$[\phi(t, z), \pi(t, z')] = \mathrm{i}\delta(z - z').$$

Are any other assumptions needed?

b) Find the equation of motion for the real scalar field $\phi = \phi(x)$, where $x = (x^\mu)$ is the 4-position vector, using the following Lagrangian

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)\left(\partial^\mu \phi\right) - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4.$$

In case the field $\phi(x)$ is reduced to a two-dimensional one $\phi(t, z)$, how will the equation of motion change and how does it compare to the one in Problem a)?

2. If the charged field $\phi = (\phi_1 + \mathrm{i}\phi_2)/\sqrt{2}$, where ϕ_1 and ϕ_2 are commuting Hermitian fields, show that the Lagrangian density for the charged field ϕ,

$$\mathcal{L} = \partial_\mu \phi^\dagger \partial^\mu \phi - m^2 \phi^\dagger \phi,$$

can be written as the sum of two *independent* Lagrangian densities

$$\mathcal{L} = \mathcal{L}_1 + \mathcal{L}_2.$$

What is the form of each density $\mathcal{L}_i$?

Part II

1. *Kaluza–Klein theory.* Assume a five-dimensional spacetime labeled by the coordinates (x, y), where $x = (x^\mu)$ are the usual coordinates of four-dimensional spacetime and y is a compact coordinate that parametrizes the extra dimension. Consider the Lagrangian density

$$\mathcal{L} = (\partial_N \phi^*)(\partial^N \phi) - m^2 \phi^* \phi,$$

where $N = 0, 1, 2, 3, 5$, $\phi = \phi(x, y)$ is complex scalar field compactified on a circle with radius R, and $m > 0$ is a mass. Since the fifth dimension is a circle, the field ϕ must be periodic in the coordinate y, i.e. $\phi(x, y) = \phi(x, y + 2\pi R)$.

a) Find the conjugate momentum $\pi(x, y)$ to the field $\phi(x, y)$.

b) Derive the free Klein–Gordon equation for the field ϕ in the five-dimensional spacetime.

Hint: Introduce

$$\Box_5 \equiv \Box - \frac{\partial^2}{\partial y^2},$$

where $\Box = \partial_0^2 - \nabla^2$ is the usual four-dimensional d'Alembertian operator.

c) Show that, from the point of view of a four-dimensional observer, this Klein–Gordon equation describes an infinite set of particles known as the Kaluza–Klein tower and compute their masses.

Hint: Use a Fourier series for the field $\phi(x, y)$ in the fifth coordinate y.

2. By making the minimal coupling

$$\begin{aligned} \partial_\mu \phi(x) &\to D_\mu \phi(x) = [\partial_\mu + \mathrm{i}eA_\mu(x)]\, \phi(x), \\ \partial_\mu \phi^\dagger(x) &\to [D_\mu \phi(x)]^\dagger = [\partial_\mu - \mathrm{i}eA_\mu(x)]\, \phi^\dagger(x) \end{aligned}$$

in the Lagrangian density of the complex Klein–Gordon field $\phi(x)$, derive the Lagrangian density $\mathcal{L}_I$ for the interaction of the charged bosons, described by the field $\phi(x)$, with the electromagnetic field $A_\mu(x)$.

Department of Physics

Homework Problems #3 in
SI2390 Relativistic Quantum Physics, 7.5 credits
Spring 2022, Period 3

Deadline: Part I: Quiz on March 7, 2022 @ 16:00–17:00
Part II: March 14, 2022 @ 16:00

Examiner: Prof. Tommy Ohlsson
(Telephone: 08-790 8261 • E-mail: `tohlsson@kth.se`)

GOOD LUCK!

Part I

1. a) For a free Klein–Gordon field ϕ, compute the following correlation functions

$$\langle 0|T[\phi(x)\phi(y)\phi(z)]|0\rangle \quad \text{and} \quad \langle 0|T[\phi(x)\phi(y)\phi(z)^4]|0\rangle,$$

where $|0\rangle$ is the ground state (vacuum) of the free Klein–Gordon theory.

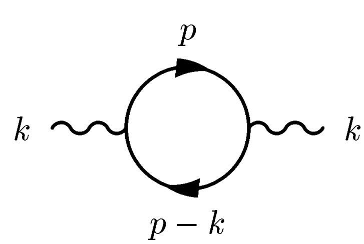
Note that the correlation function $\langle 0|T[\phi(x)\phi(y)\phi(z)^4]|0\rangle$ would only appear within an interacting theory, but this correlation function can still be computed.

b) For a free Dirac field ψ, compute the following correlation functions

$$\langle 0|T[\psi(x)\psi(y)\psi(z)]|0\rangle \quad \text{and} \quad \langle 0|T[\psi(x)\psi(y)\bar{\psi}(z)\bar{\psi}(w)]|0\rangle,$$

where $|0\rangle$ is the ground state (vacuum) of the free Dirac theory.

2. *Photon self-energy.* Write down the amplitude for the Feynman photon self-energy diagram shown in the following figure:



Part II

1. *Decay of a scalar particle.* Consider the following Lagrangian, involving two real scalar fields Φ and ϕ:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi - \frac{1}{2}M^2\Phi^2 + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2}m^2\phi^2 - \mu\Phi\phi^2.$$

The last term is an interaction that allows a Φ particle to decay into two ϕ particles, provided that $M > 2m$. Assuming that this condition is fulfilled, calculate the lifetime of the Φ particle to lowest order in the coupling constant μ.

2. *Pseudoscalar Yukawa theory.* One part of the interaction Lagrangian for pseudoscalar Yukawa theory is given by

$$\mathcal{L}_{PY,\,\text{int.}} = -\mathrm{i}g\bar{\psi}\gamma^5\psi\phi,$$

where ϕ is a neutral Klein–Gordon field, ψ is a Dirac field, and g is the coupling constant of the interaction. Using dimensional regularization, determine the one-loop vertex correction to this interaction. In addition, calculate the counterterm δg.

Resultat av: Relativistic Quantum Physics, SI2390, vt 2022

Status: Avslutad
Publicerad under: 2022-03-15 - 2022-03-25
Antal svar: 19
Procent av kursdeltagarna som svarat: 82%
Kontaktperson: Tommy Ohlsson

What is your overall impression of the course?

19 svarande

Very positive	6	31%
Quite postive	11	57%
Neutral - no opinion	1	5%
Quite negative	1	5%
Very negative	0	0%

- *Really interesting course leading to a first understanding of QFT and Particle Physics. I enjoyed the lectures very much. Were there more descriptions and interpretations of the actual physical phenomenons, the course would be perfect. It feels sometimes as the content seems very abstract and needs some physical interpretation and examples. (Very positive)*
- *In general, I liked the course a lot. I felt that it made me "evolve" as a physicist. (Very positive)*
- *I think on a scientific point of view, this course was the most difficult one that I have ever follow. However it was extremely interesting. (Very positive)*
- *Very interesting course, maybe a bit too fast for me. I sometimes felt a bit drowned in the amount of information. (Quite postive)*
- *This course touches on some very interesting topics, and there is beauty to the mathematical rigor involved in the field. Although, I am very dissatisfied with the course literature. More on this below. (Quite postive)*

- I am very glad I learnt a lot of things, however I felt that sometimes the lectures did not focus enough on the physical concepts and were a bit hard to follow since we didn't know why we were computing things. I think that beginning the lecture with a quick reminder of what we are physically talking about would be very useful. (Quite postive)
- overall i thought that the pace was too fast in the sense that we simply glossed over very important aspects. I would say we would have needed at least 4 more lectures to fully grasp the theory of QED and its corrections (Quite negative)

How would you rate the difficulty of the course?

19 svarande

Very difficult	5	26%
Quite difficult	11	57%
Average	3	15%
Easy	0	0%
Very easy	0	0%

- I had to spend at least 5 hours for every course done in class to be sure I understood the content of it and the calculations. The assignements also required a lot of work for me. (Very difficult)
- I do not think the course is such difficult, but the duration of the period to learn all of this seemed quite short to me. (Quite difficult)
- In particular, I have found the homework problems quite hard. Maybe a few smaller problems with easier difficulty (and with solutions) could help preparing students for the harder ones. (Quite difficult)
- I had never done relativity theory so I had to catch up at the beginning but wasn't so hard to catch up. The notions are not easy but this is challenging and I enjoyed it a lot! (Quite difficult)
- Difficult in a good way. The subject is not easy per se. It required a lot of thinking and time on my own to let the knowledge sink in. (Quite difficult)
- This goes with the above. Since the pace was too high we could not go into enough detail and we only scratched at the surface (Average)

Has there been much overlap with other courses?

19 svarande

Far too much overlap	0	0%
Some overlap, but it was useful to go over the topics again	14	73%
Mostly unnecessary overlap	0	0%
No overlap	5	26%

- I appreciated to work several times on the same topics, often with a different point of view. (Some overlap, but it was useful to go over the

topics again)
- Some crucial overlap with Special relativity but also some with Analytical mechanics which most people have not taken (Some overlap, but it was useful to go over the topics again)
- There was a bit of overlaps with the experimental particle physics course that I was following at the same period but it was all for the best since the relativisitic quantum mechanics one was going deeper into details. (Some overlap, but it was useful to go over the topics again)
- Being an exchange student in first year of Master, there were no overlap whatsoever with my previous courses. I was introduced to entirely new concepts! (No overlap)
- N/A (No overlap)

How were the quizzes?

19 svarande

Very difficult	0	0%
Difficult	6	31%
Average	13	68%
Easy	0	0%
Very easy	0	0%

- For the final quiz (especially) the preparation questions prepared us for the quizzes. This I think should be addressed in some sense, perhaps the quizzes should point us more in the direction of what details in book we were expected to learn. (Difficult)
- Some questions were a bit tricky and uneasy to understand, it was hard sometimes to understand what the professor wanted us to say. (Difficult)
- We could prepare with the homework, but there were still some questions about a deeper understanding, which was is point point to me. (Average)
- The quizzes' difficulty is perfect in my opinion. (Average)
- If one had solved the exercises correctly, these were fair. (Average)
- As Tommy said "You should be fine if you made the homework and thought about the problems for a while". Which is what happened. (Average)

How were the (hand-in) homework problems?

19 svarande

Very difficult	1	5%
Difficult	17	89%
Average	1	5%
Easy	0	0%
Very easy	0	0%

- The first two assignments were quite manageable. But the third one was far too difficult in my opinion. This is in part due to the quality of the explanations in the book. (Very difficult)
- I would say the homework problems became more difficult but definitely not impossible. I would have appreciated to have every useful concept defined beforehand though. (For example, the "counterterm delta g"). (Difficult)
- Especially the last one. (Difficult)
- I think it is good that the homework problems requires a bit of work, it helps to understand better the courses. (Difficult)
- Again, difficult in a good way. They made me ponder on the "basic principles" each and every time, which is indeed a good thing. (Difficult)
- Some of them were very difficult (Difficult)
- I had to spend a lot of time doing those also but it was really interesting; all the more when they were letting me having a better understanding of the course. (Difficult)

How was the oral examination?

19 svarande

Very difficult	0	0%
Difficult	3	15%
Average	8	42%
Easy	7	36%
Very easy	1	5%

- When one has never done an oral examination before, it was really hard to know what was excepted of us. And what to work to be ready for it. (Difficult)
- Very fair. No complaints here. (Average)
- I studied a lot for the oral examination, so it was natural for it to be "average". I read the book from start to end more than one time during the course. (Average)
- I felt like Tommy was very nice at helping us along when we struggled. (Average)
- No problem with the oral examination. (Easy)

What is your opinion about the course description and the administration of the course?

19 svarande

Very good	9	47%
Good	6	31%
Average	4	21%
Poor	0	0%
Very poor	0	0%

- Like in general relativity, the canvas page is very clear and complete, we can not miss any information! (Very good)

What is your opinion about the course literature?

19 svarande

Very good	4	21%
Good	6	31%
Average	4	21%
Poor	4	21%
Very poor	1	5%

- I worked a lot with the book and it's really complete. (Very good)
- The book is very complete, however I would have appreciated to have the lecture notes which could have made easier to focus on the most important points of the courses. (Good)
- Sometimes too concise, but overall quite ok to follow. (Good)
- One of the main problems with this book is that it lacks structure. I felt overwhelmed with information between the lines of each equation, motivations were seldom clear and rigorous, steps in important calculations were sometimes left out, new terminology was used as if already known, and the list goes on. This book, while it indeed covers the intended material, certainly does not deliver it well. It was very frustrating to use, and one could then argue that other course literature was recommended by the professor at the beginning of the course. But it is not trivial to extrapolate between different literature, and this takes time. Furthermore, they might approach a problem completely differently, and so if a certain derivation or method is unclear in one book, another might not contribute with any new information. All in all, I think the coursebook needs to be thoroughly rewritten so that it has a clear structure and does not present the information as if the reader is already comfortably familiar with it. (Very poor)

How were the lectures?

17 svarande

Very good	5	29%
Good	9	52%
Average	3	17%
Poor	0	0%
Very poor	0	0%

- As I said before, beginning with a quick reminder on the physical aspects of the course we are about to have would be nice. (Good)
- I would have liked lecture notes though it would have made me read less of the actual book. (Average)

How were the seminars?

16 svarande

Very good	1	6%
Good	7	43%
Average	5	31%
Poor	3	18%
Very poor	0	0%

- I definitely find the current idea of the seminars relevant. However, I think it would make sense to finish the exercises we start, even if some help from the lecturer is needed. I found it quite frustrating not to finish the exercise about the m^{mu u lamdba} tensor. (Good)
- I did not attend any of the seminars, unfortunately. (Average)
- I only attended one (Average)
- Personally, I would like the normal structure of a seminar. (Poor)

Please enter any further comments on the course below.

- The physics in this course is very cool. I am glad to have studied such a fascinating course! I will make sure to deepen my knowledge further in the future when I have more time. Thank you!
- It would have been nice if the lecture notes were available online. It felt a bit exclusive when one only had the book to lean against when missing a lecture due to health issues.
- Thanks a lot for this course, it was really interesting !
- I would suggest make it a two period course of 10 ects. Then we. ould have more hand in assignments and have a deeper look into the later important QED topics
- It's a bit sad that they were only two girls in that course. I know it's not your fault but I would have preferred if there were more of us

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