Semester 2: Choose 4 courses (4 credits each), see the general FunPhys curriculum

Chimie pour l'Agrégation-S2

Chimie pour l'Agrégation

Contacts: B. Guigliarelli & I. Beurroies

UE destinée à assurer la transition du parcours Physique vers la Préparation à l'Agrégation de Physique-Chimie et pour les physiciens souhaitant garder un lien avec les sciences de la matière.

I- Structure de la matière

Structure électronique des atomes et molécules. Complexes d'ions de transition, théorie du champ cristallin, propriétés spectroscopiques et magnétiques. Structure des solides cristallins. Exploitation des données structurales.

II-Thermodynamique des transformations physiques et chimiques

Caractérisation des états d'un corps pur et de mélanges et de leurs changements d'états. Diagramme de phase. Diagramme binaire.

Thermochimie. Analyse d'un état d'équilibre chimique et des transformations chimiques. Evolution d'un système sous l'influence des variations de paramètres physiques (T, P) ou de composition (système ouvert).

III- Chimie des solutions

Solvants et solutés, mécanismes de solubilisation, polarisation, forces de Van der Waals, liaisons hydrogènes. Transformations chimiques en solution, précipitation-solubilisation, réactions acide-base, complexation, oxydo-réduction. Méthodes d'analyse et de caractérisation, dosages et titrages, conductimétrie, spectroscopies, électrochimie, électrodes de mesures, courbes intensité-potentiel.

IV-Cinétique chimique

Modélisation des cinétiques de transformations chimiques, méthodes d'études expérimentales. Energie d'activation, effets isotopiques. Catalyse en phase homogène, en phase hétérogène, mécanismes réactionnels.

V- Domaines d'application

Stockage d'énergie, chimie analytique, toxicologie, corrosion, élaboration.

Statistics and Data Analysis-S2

Statistics and Data Analysis

Contacts: H. Costantini or C. Schimd

Programme:

1. Basics of probability
Axiomatics, frequentist, and Bayesian probability. Discrete and continuous random variables, cumulative and probability distribution function (pdf); conditional and marginalised probability, Bayes formula. Some pdf: uniform, Gaussian, t-Student, chi-square, binomial, Poisson. Central limit theorem, inequalities. Random vectors, covariance matrix, multi-variate pdf. Moments, characteristic function. Transformation of random variables.

2. Basics of statistics
Descriptive statistics; KDE, MEM. Parameters' estimation: methods of maximum likelihood and minimum chi-square; linear regression. Error propagation, confidence intervals, correlations. Test of hypothesis, likelihood ratio, odd ratio, statistical tests (chi-square, t-Student, Fisher-Snedecor). Fisher information matrix. Jackknife, bootstrap.

3. Stochastic processes and optimisation
Time series, Markov process, spatial processes and random fields in 2, 3, and N dimensions. Power spectral density, correlation functions, Wiener-Khintchine theorem. Stochastic differential equations, AR process, Yule-Walker equation, Kalman filter, Feynman-Kac formula. Deterministic optimisation: steepest descent, conjugate gradient, Levenberg-Marquard. Stochastic optimisation: Markov chain Monte Carlo (MCMC), Hamiltonian Monte Carlo, simulated annealing, parallel tempering, importance sampling.

4. Spectral and multivariate analysis: sampling, deconvolution, filtering, classification
Orthogonal polynomials (shapelets, Zernike), Fourier transforms (DFT, FFT, WFT). Sampling: Nyquist-Shannon theorem, periodogram. Integral transforms, Fredholm and Volterra integral equations, Fredholm alternative, resolvent and Nystrom methods, Richardson-Lucy deconvolution. Inverse problem: optimal (Wiener) filtering, regularisation methods (zero-order, Tikhonov/ridge regression). Karhunen-Loève transform, principal component analysis (PCA), linear discriminant analysis (LDA).

Exercise sessions:

- Poisson statistics: counting experiments with background.
- Histograms, kernel density estimator (KDE), maximum entropy method (MEM).
- Fitting a polynomial, fitting a straight line with errors in both variables. Goodness-of-fit.
- Errors by jackknife, bootstrap, Monte Carlo synthesis.
- Scattering: numerical solution of Volterra equation.
- Tikhonov regularisation and differentiation of noisy data.
- Kalman filtering: tracking particles in a detector or satellites in the sky.
- Image restoration by Wiener filtering.
- PCA: classification of galaxy spectra, image compression.

References:

- Cowan, Statistical Data Analysis (Oxford Science Publications)
- Stark & Murtagh, Handbook of Astronomical Data Analysis (Springer)
- Van Kampen, Stochastic Processes in Physics and Chemistry (Springer)
- Numerical Recipes in Fortran/C/C++

Plamas Physics - S2

Plasma Physics

Contacts: O. Peyrusse & P. Beyer

Preliminaries : Reminder on Maxwell's equations, macroscopic fields

General considerations on classical plasmas

- Plasma frequency, Debye length
- Microscopic (corpuscular) formulation

Kinetic formulation

- Concepts of kinetic theory, Liouville equation
- Equation for the one-particle distribution function
- Vlasov and Boltzmann equations, notion of collision operator

Fluid Formulation

- Derivation of fluid equations from kinetic theory
- Plasma as a mixture of 2 fluids

Electronic plasma waves

- Plasma Oscillations : fluid approach
- Plasma Oscillations : kinetic approach (Landau damping)

Collision phenomena in plasmas

- Preliminary: kinematic analysis, dynamic analysis of a Coulombian scattering event
- Collisions between corpuscles in plasmas
- Characteristic collision frequencies in maxwellian plasmas

Electromagnetic waves in plasmas

- EM wave without external magnetic field in a cold plasma
- EM wave with external magnetic field in a homogeneous plasma – propagation perpendicular to B, parallel to B. Application to Faraday rotation.

Radiation mechanisms in plasmas

- Emission and absorption mechanisms (atomic transitions, recombination radiation, Bremsstrahlung)
- Population of energy levels (laws of the local thermodynamic equilibrium, collisional-radiative equilibrium)

Trajectory of a charged particle in a magnetic field

- Cyclotronic movement and drift
- Confinement geometries (magnetic bottle, toric configurations)

Introduction to Thermonuclear Fusion

- Nuclear reactions; reaction rates

- Power balance; ignition, Lawson criterion

Charged Fluids Dynamics (S2)

Charged Fluids Dynamics

Contact: O. Agullo

1. CHARGED PARTICLES IN AN ELECTROMAGNETIC FIELD: MHD
Elements of kinetic theory: velocity, pressure and temperature.
Two-fluid model,
One-fluid model, quasi-neutrality, validity of the model
Magnetic diffusion, magnetic Reynolds number

2. IDEAL MHD
Energy conservation within ideal MHD
Alfvén theorem: Magnetic flux conservation, Frozen-in properties
Magnetic helicity and topology, Invariants

3. MHD WAVES
Magnetosonic and Alfvén waves.

4. MHD Equilibria
Magnetic pressure
Cylindrical equilibria: theta-pinch, z-pinch, screw-pinch
Planetary magnetospheres (Ferraro's theorem)

5. MHD INSTABILITIES (in confined plasmas, space and astrophysical plasmas)
Instabilities induced by a pressure/thermal gradient (Rayleigh-Bénard, Rayleigh-Taylor)
Magneto-rotational instability and application to star accretion disks

6 INTRODUCTION TO DYNAMO
Different mechanisms of dynamo
Robert's dynamo, anti-dynamo theorem
Experiments: Riga, Von Karman sodium (VKS)
Applications: solar dynamo and terrestrial dynamo

Modern Astrophysics-S2

Étoiles & Exoplanètes / Stars & Exoplanets

Contacts: D. Burgarella, M. Pieri, and A. Zavagno

This lecture is based on active learning. The students will perform 3 compulsory supervised projects.

I. Basics of astronomy

- The cosmological distance ladder
- Relative motions
- Luminosity and apparent brightness
- Stellar spectra
- The H-R diagram, the main sequence
- Stellar classification

II. Star and planet formation

- Star and planet formation
- Basic stellar physics (radiative transfer)
- Planet formation: some key open questions
- Binaries
- Stars in clusters
- Star chemical composition
- Star properties

III. Stellar evolution and observables

- Main parameters controlling the stellar populations
- Stars and stellar populations in the universe
- Stars and the rise of metals in the universe
- Modelling stellar populations

Cosmology-S2

Cosmology

Contact: Pr. Philippe Amram

- Introduction to cosmology
- General Relativity
- Friedmann-Lemaître models
- Properties of Friedmann-Lemaître models
- Project (choose 1 project from a list of 4 proposals)

Motivation:the goal of this optional lecture is to introduce general relativity and the subsequent main models of the Universe and tests in observational cosmology.

I. The main observations of the Universe.

1. Radiation and observations.The observables and their interpretation.
2. Distribution of the observed matter in the Universe. The baryonic matter: direct and indirect observations
3. The dark matter and the dark energy
4. The three pillars of cosmology :galaxies recession, cosmological radiation, elementary particles and primordial nucleosynthesis

II.General relativity

1. Tensors calculations
2. Operators,frame transformations, Christoffel symbols, differential
3. Curve spaces Metric tensors, geodesic tensors, curvature tensors, Einstein tensors
4. Einstein equations

- The principles (equivalence, cosmological, Mach,general relativity,covariance).
- Tensor
- Energy-momentum
- Complete formulation of the Einstein equations

III. The Friedmann --Lemaître models

1. Expression of the four-dimension metric dimension
2. Christoffel symbols. Ricci tensor.Scalar curvature.
3. Energie-momentum tensor and Einstein equations
4. Expression of the general relativity equations in the Robertson-Walker metric
5. Unvarying models at null cosmological constant

IV. Properties of the Friedmann--Lemaître models

1. Observational tests and evolution of the Universe distances, age, Hubble constant, spectral shifts, deceleration parameters, scaling factors, time, energy density, temperature, entropy.
2. The standard model : successes and difficulties
3. Inflationary models

V. Introduction to the standard model

1. The new cosmological tests :anisotropy and cosmological background, baryonic acoustic oscillations, far supernova and gravitational shear
2. The cosmological parameters and precision cosmology. Acceleration of the Universe.
3. The Universe contents : baryons, dark matter, dark energy
4. Structure of the Universe: Amplitude of fluctuations, spectral index, reionization epoch.
5. Formation of the first stars and galaxies.

Relativité-Relativity-S2

Relativité / Relativity

Contact: Alexandro Perez

Special Relativity:

1) Introduction and Motivation: the relativity of motion, Galileo transformations, assumptions.
2) Electromagnetism and the speed of light form Maxwell Equations.
3) Maxwell equations from an action principle.
4) Lorentz Transformations as the fundamental symmetry of electromagnetic interactions.
5) Tensor, vectors: physics in terms of inertial coordinates and beyond.
6) Maxwell equations in tensor notations.

General relativity:
1) The relativity of inertial forces: The equivalence principle, gravity as geometry.
2) Tensor, vectors on curved spacetimes
3) More basic elements of differential geometry:
covariant derivatives, parallel transport, geodesics, curvature.

4) Derivation of Einsteins equations
5) Cosmological solutions: the FLRW solutions (elements of the standard model of cosmology).
6) The static spherical solution: a spherical star in GR, the Schwarzshild Black Hole solution.
7) Gravitational waves.
8) Gravitational wave detection.

Physique des Particules, Physique subatomique-Subatomic and Particle Physics-S2

Physique des Particules, Physique subatomique / Subatomic and Particle Physics

Contact: J. Busto, J-P. Ernenwein & M. Talby

Subatomic Physics I - Introduction to physics of the atomic nucleus (10h)
- Structure of the nucleus: Mass, Radius, Binding Energy, Abundances
- Nuclear models: liquid drop, Fermi gas model, shell model
- Instability of matter: radioactivity and decay modes
- Nuclear reactions: fission, fusion

Subatomic Physics II – Applications (6h)
- Radioactive dating, tracers, imaging. Production of energy
- Radiation protection
- Nuclear Astrophysics

Particle Physics I – Introduction (4h)
-Particles and interactions
-System of natural units

Particle Physics II - Symmetries and conservation laws (8h)
-Notions of symmetry and conservation: total angular momentum, electric charge,
lepton and baryon numbers, flavor, Isospin, parity, charge parity.
-Application to particle decay ; basic notions on Feynman diagrams, aiming at representing the transition between initial and final states.

Particle Physics III - Hadrons: static quark model (4h)
-Mesons
-Baryons.

Particle Physics IV – Relativistic kinematics, cross-section and decay rate (8h)
- Context of special relativity. Four-vector formalism and Lorentz transformation
- Laboratory frame, center of mass frame ; Mandelstam variables
- Computation of the decay rate of a particle, mean lifetime
- Computation of the scattering cross-section

Application of the acquired knowledge: a part of the grade will be given for a study conducted by the student on items related to the course.

References

- Luc Valentin, Le Monde subatomique : des quarks aux centrales atomiques, Hermann (1986)
- F. Halzen & A.D. Martin, Quarks and Leptons, John Wiley & Sons (1984),
- André Rougé, Introduction à la Physique Subatomique, éditions Ellipses (1997),
- Benoit Clément, Physique des particules: Cours et exercices corrigés, Dunod 2013

Spectroscopie, Imagerie, Détection / Spectroscopy, Images, Detection-S2

Spectroscopy, Images, Detection

Contact: T. Angot

Classical approach of radiation

- Emission of an electromagnetic wave, classical electric dipole radiation, synchrotron
- radiation
- Absorption and scattering, lineshape, dielectric function
- Optical properties of materials and spectroscopies
- Vibrational and electronic energy levels
- in atoms, molecules and solids
- Absorption and emission spectroscopies, Fermi
- golden rule
- Elementary collective excitations in solids
- (phonon, plasmon, exciton)

Elastic and Inelastic scattering

- Coherence, diffraction by a crystal, inelastic scattering
- Basic theory of Lasers

Images

- X-ray Imaging, tomographie. Sound and ultrasound imaging.

Advanced Mathematical Methods

Advanced Mathematical Methods

Contact: S. Lazzarini & F. Piazza

Group theory (20 Hrs)

- Groups: Discrete or Continuous, Finite or Infinite
- Representing Group Elements by Matrices

- Group Theory in the Microscopic World
- Linearization: Lie algebras
- Symmetry in the Laws of Physics: conserved quantities (Noether)
- SU(2): Double Covering of SO(3) and the Spinors
- Isospin and the Discovery of a Vast Internal Space: The Eightfold Way of SU(3)

Differential geometry (20 Hrs)

- Differential forms
- Application to electromagnetism / gradients, curl and divergence
- Differential Calculus on Manifolds
- Vector and covector fields / Differentiating tensors / Exterior calculus / Physical applications / Covariant derivatives / Metric manifolds
- Fibre Bundles: When differential geometry and group theory meet each other.

References
[1] M. Stone and P. Goldbart ”Mathematics for Physics A guided tour for graduate students”, Pimander-Casaubon (2008), http://www.goldbart.gatech.edu/PostScript/MS PG book/bookmaster.pdf
[2] A. Alastuey, M. Magro, P. Pujol , ”Physique et outils mathématiques : méthodes et exemples”, EDP sciences (2008)

[3] A. Zee, « Group Theory in a Nutshell for Physicists », Princeton University Press, 2016

Systèmes Dynamiques-Dynamical Systems-S2

Systèmes Dynamiques / Dynamical Systems

Contact: A. Pocheau & J. Deschamps

Motivations:

This course aims to show, in simple contexts, how determining the possible evolutions of a dynamical system, especially at long time, depending on the system parameters. The approach is thus both global (for all initial conditions) and parametric (for a range of parameters).

The **objective** is to:

1. determine states (fixed points, limit cycle) that structure the dynamics ; use them to determine the system’s evolutions.
2. show how change of parameters can change the structure of the dynamics ; learn how to identify them.

The systems will be modelled by ordinary differential equations. They will address both familiar systems (e.g. linear or non-linear oscillators) or new systems (e.g. population dynamics). Attention will be laid on global approaches (phase portrait) and structural concepts (attractors, stability/instability, bifurcation point).

I] Linear Systems

- evolution operator, Jordan reduction
- eigenmodes, secular modes, existence and uniqueness of solutions
- phase portrait, fixed points, attractors

II] Non-linear Systems

- Tools and methods (linearization, orbits, invariants, symmetries, perturbative expansions, multiplicity, finite-time divergence …)
- Phase portraits (pendulum, population dynamics, epidemics, …)
- Flow dynamics (trapping domain, limit cycle, Poincaré-Bendixson criterion, Dulac criterion, Lyapunov function, gradient systems , …)

III] Introduction to bifurcations

- Nature of bifurcations
- Examples of bifurcation (pitchfork , transcritical, …)

This course provides a valuable preparation to the S3-course « Dynamical System and Non-Linear Physics ».

Milieux Continus-Continuous Media-S2

Milieux Continus / Continuous Media

Contact: A. Pocheau & J. Deschamps

Motivations: The course addresses the dynamics of deformable continuous media, especially fluid media, including their kinematic description and their transport and exchange phenomena. It aims at identifying the dynamical regimes, the specific features of flows and their main implications.

The tools for describing the continuous media will include strains, kinematics (strain rate, vorticity, shear) and geometry (streamlines and stream functions, trajectories). Then advective or diffusive fluxes of scalar or vectorial quantities (impulsion) will be introduced and modelled by the Fourier law or the Fick law. The dynamical budgets of these quantities in eulerian or lagrangian control volume will provide constitutive differential equations (Navier-Stokes, Fourier, Fick).

Analysis of the dynamics will begin by geometrical and dynamical similarity and yield essential non-dimensional numbers (Reynolds, Péclet). The viscous Stokes regime will be addressed in Hele-Shaw cells, Poiseuille flows, boundary layers and porous media in link with reversibility/irreversibility concepts.

The inviscid fluid regime will be addressed by the Euler equation, the Bernoulli relation, and potential flow. Conformal mappings will be applied to deduce flows around bodies and the resulting forces.

The vorticity dynamics will be considered in analogy with electromagnetism and will yield strain/diffusion dynamics, the Kelvin theorem and the d'Alembert paradox.

This course provides a valuable preparation to the S3-courses « Dynamical System and Non-Linear Physics», « Soft Matter » and to the « concours de l'agrégation de physique-chimie, option physique ».

I] Foundation

- description of continuous media : deformation, kinematics, geometry.
- modelling of exchange and transport phenomena (flux of scalar/vectorial quantity, stress, viscosity)
- budget equations : Euler/Lagrange formulation, Navier-Stokes equation, Fourier/Fick equations, incompressibility.

II] Developments

- geometrical/dynamical similarity.
- Stokes regime, perfect fluid, potential flows.
- vorticity, planar boundary layers, applications.

Physics of Living Systems I - (S2)

Physics of Living Systems I

Contact: Pierre-François Lenne

The objective of this course is to introduce the physical principles underlying the organization and dynamics of living systems. Biological organisms display a complex organization, with substructures organized over all length scales, from the molecule, to the cell, to the tissues, to the whole organisms. Their dynamics is rich: their cells can multiply and differentiate into different types supporting distinct functions. They can respond to variations of external conditions, remodel and reshape parts of their body during development or accidental damage, and reproduce themselves endlessly. Despite their unique capabilities, living systems do no evade the principles of physics. This course will show how living systems can be described, studied and understood thanks to the concepts and technologies from different domains of physics. After an introduction on the building blocks of living systems, the course will cover the following topics:

Energy and Information

- Synthesis of biomolecules, energy production and storage
- Entropic forces
- Chemical forces and self-assembly
- Polarity

Molecular motors in the cell

- Mechanochemical machines
- Active polymers
- Cell motion

Mechanics of cells and tissues

- Cell shape
- Cell division
- Tissues as viscoelastic active materials

Shapes of the living systems

- Emergence of shapes
- Body plan (reaction-diffusion, pattern formation)

20 hours Lectures / 16 hours TD / 4 hours conferences

Lecturers: Pierre-François Lenne, Pierre Recouvreux, Félix Rico (?)

Evaluation: written

Condensed Matter Physics-S2

Condensed Matter Physics

Contact: A. GHORAYEB & Olivier THOMAS

Content:

I Brief reminder of the free-electron model

Usefulness and failures

II Electrons in crystals : band theory

II.1 Nearly-free electrons

Electron levels in a periodic potential, Bloch's theorem, crystal momentum, band index, energy bands, Fermi surface

II.2 Tight-binding theory

Linear combination of atomic orbitals, application to bands from s-levels

III Semiconductors

Homogeneous semiconductors in thermal equilibrium, examples of semiconductor band structure, intrinsic and extrinsic semiconductors, impurity levels, p-n junction in equilibrium

IV Magnetic properties

Diamagnetism and paramagnetism, Curie's law, electron interactions and magnetic structure, magnetic ordering, ferro- and anti-ferro-magnets

V Properties at the nanoscale

Density of states in low-dimensional (2D, 1D, 0D) systems and nanostructures, ballistic transport and quantization of conductance, the Landauer formula, examples of low-dimensional structures

VI Introduction to superconductivity

Critical temperature, critical field, Cooper pairs, the London equation

Main textbooks :

N. W. Ashcroft and N. D. Mermin, Solid State Physics, Saunders College Publishing, 1976, ISBN 0-03-049346-3 (international edition).

M. L. Cohen and S. G. Louie, Fundamentals of Condensed Matter Physics, Cambridge University Press, 2016, ISBN 978-0-521-51331-9 (hardback).