

# Nuclear Physics

Master in Physics / Master in Engineering Physics

1<sup>st</sup> Year, 1<sup>st</sup> Semester

2026–2027

# Rui Santos

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Room: 8.5.16

## When

- Tuesdays
  - T-Class: 16h00 – 17h00
  - Room: 8.2.04
- Fridays
  - T-Class: 8h30 – 9h30
  - TP-Class: 9h30 – 10h30
  - Room: 6.2.40

# Calendar

1<sup>st</sup> Semester 2026-2027  
(About 14 weeks of lectures)

| September 2026 |     |     |     |     |     |     |
|----------------|-----|-----|-----|-----|-----|-----|
| Mon            | Tue | Wed | Thu | Fri | Sat | Sun |
|                | 1   | 2   | 3   | 4   | 5   | 6   |
| 7              | 8   | 9   | 10  | 11  | 12  | 13  |
| 14             | 15  | 16  | 17  | 18  | 19  | 20  |
| 21             | 22  | 23  | 24  | 25  | 26  | 27  |
| 28             | 29  | 30  |     |     |     |     |

| October 2026 |     |     |     |     |     |     |
|--------------|-----|-----|-----|-----|-----|-----|
| Mon          | Tue | Wed | Thu | Fri | Sat | Sun |
|              |     |     | 1   | 2   | 3   | 4   |
| 5            | 6   | 7   | 8   | 9   | 10  | 11  |
| 12           | 13  | 14  | 15  | 16  | 17  | 18  |
| 19           | 20  | 21  | 22  | 23  | 24  | 25  |
| 26           | 27  | 28  | 29  | 30  | 31  |     |

| November 2026 |     |     |     |     |     |     |
|---------------|-----|-----|-----|-----|-----|-----|
| Mon           | Tue | Wed | Thu | Fri | Sat | Sun |
|               |     |     |     |     |     | 1   |
| 2             | 3   | 4   | 5   | 6   | 7   | 8   |
| 9             | 10  | 11  | 12  | 13  | 14  | 15  |
| 16            | 17  | 18  | 19  | 20  | 21  | 22  |
| 23            | 24  | 25  | 26  | 27  | 28  | 29  |
| 30            |     |     |     |     |     |     |

| December 2026 |     |     |     |     |     |     |
|---------------|-----|-----|-----|-----|-----|-----|
| Mon           | Tue | Wed | Thu | Fri | Sat | Sun |
|               | 1   | 2   | 3   | 4   | 5   | 6   |
| 7             | 8   | 9   | 10  | 11  | 12  | 13  |
| 14            | 15  | 16  | 17  | 18  | 19  | 20  |
| 21            | 22  | 23  | 24  | 25  | 26  | 27  |
| 28            | 29  | 30  | 31  |     |     |     |

## Schedule

 T-Class (Tuesdays)  
16h00 – 17h00  
Room: 8.2.04

 T + TP Classes (Fridays)  
T-Class: 8h30 – 9h30  
TP-Class: 9h30 – 10h30  
Room: 6.2.40

## Exam dates

 1<sup>st</sup> exam date (test)  
12 January 2027

 2<sup>nd</sup> exam date  
8 February 2027

 Resit exam  
22 February 2027



# Program

## Topics

1

### Ground State Properties

- Nuclear structure and binding energy
- Nuclear radioactivity:  $\alpha$ ,  $\beta$  and  $\gamma$  decays

2

### Nuclear Reactions

- Reaction kinematics and cross sections
- Direct and compound reactions

3

### Nuclear Energy

- Nuclear fission and reactors
- Nuclear fusion and future perspectives

4

### Nuclear Astrophysics

- Nucleosynthesis in the Big Bang, stars and stellar explosions
- Key nuclear reactions and reaction rates



# Evaluation and Materials

## Evaluation

The course assessment consists of two components:

|     |                                                              |
|-----|--------------------------------------------------------------|
| 30% | Oral Presentation<br>(optional, best grade normalised to 20) |
| 70% | Final Written Examination                                    |

A minimum grade of **10 out of 20** is required for the written examination in order to pass the course.

The exam is open book and no electronic devices are allowed anywhere near the student.

## Presentation grading

The presentation grade will be distributed as follows:

|     |                                                 |
|-----|-------------------------------------------------|
| 30% | Scientific content                              |
| 40% | Quality and clarity of the oral presentation    |
| 30% | Discussion and your ability to answer questions |

## Oral Presentation

Each student must propose a topic and deliver an individual presentation on **24 November**.

Presentations will have a maximum duration of **20 minutes**, including approximately **5 minutes for questions and discussion**.

The students may choose any topic of nuclear physics or in its relation to particle physics or cosmology.

The deadline for topic selection is **10 November**.

## Materials

All course materials will be available in Fenix.

## Use of AI tools

Students are encouraged to use AI tools; this reflects my personal view. Any use of AI must not replace your own critical thinking and analysis.

# And before we start

Lectures will begin **10 minutes** after the scheduled start time. I will be available during those **10 minutes** to answer questions about the previous lecture. Once the lecture has started, students will not be permitted to enter the classroom.

- Listening to Radiolab – <https://radiolab.org/>
- Watch Veritasium – <https://www.youtube.com/veritasium>

# Bibliography

- **Introductory Nuclear Physics**  
K. S. Krane, John Wiley & Sons, 1988
- **Nuclear Physics in a Nutshell**  
C. A. Bertulani, Princeton University Press, 2007
- **Nuclear Physics (Física Nuclear)**  
Theo Mayer-Kuckuk, Fund. Calouste Gulbenkian, 1993
- **Nuclear Physics of Stars**  
C. Iliadis, Wiley-VCH, 2007
- **Cauldrons in the Cosmos**  
C. E. Rolfs & W. S. Rodney, Univ. of Chicago Press, 1988



# Elementary particles

## Quarks

(feel the strong, weak and electromagnetic interactions)



up



charm



top



down



strange



bottom

## Leptons

(feel the weak and electromagnetic interactions)



electron



muon



tau



electron  
neutrino



muon  
neutrino



tau  
neutrino

## Force carriers

(mediate the fundamental interactions)



photon

electromagnetic  
interaction



gluons

strong  
interaction



W bosons

weak  
interaction



Z boson

weak  
interaction

## Scalar boson



Higgs boson

gives mass  
to particles

## The Standard Model

The elementary particles are the fundamental building blocks of matter and the carriers of the fundamental interactions.

They are grouped into quarks and leptons, which form matter, and force carriers, which mediate the interactions between particles.

The Higgs boson is associated with the mechanism that gives mass to elementary particles.

**All the visible matter in the Universe is built from these elementary particles and their interactions.**

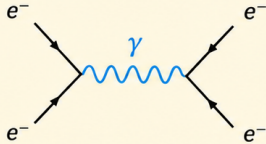
# How do particles interact?

Particles interact through the exchange of force carriers. Each fundamental interaction has its own mediator and acts on specific types of particles.

## Electromagnetic interaction

Mediated by photons ( $\gamma$ )

*Acts on particles with electric charge*

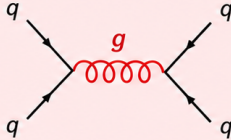


- Infinite range
- Responsible for electromagnetic phenomena (electricity, magnetism, light)
- Acts on quarks and charged leptons

## Strong interaction

Mediated by gluons ( $g$ )

*Acts on particles with colour charge*

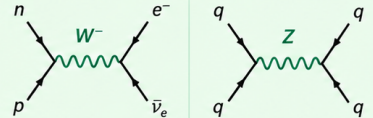


- Short range (confined inside hadrons)
- Strongest of the fundamental interactions
- Acts on quarks (and gluons)
- Responsible for binding quarks into protons, neutrons and other hadrons

## Weak interaction

Mediated by  $W^+$  and  $Z$  bosons

*Acts on quarks and leptons*



**Charged current**  
(e.g.  $\beta$  decay)

**Neutral current**  
(e.g. neutrino scattering)

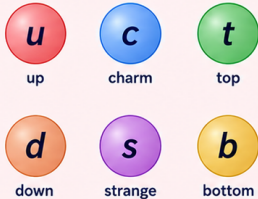
- Very short range
- Responsible for radioactive decay
- Changes the flavour of quarks and leptons
- Acts on all quarks and leptons

**The fundamental interactions determine the behaviour of matter at all scales, from the smallest distances to the structure of the Universe.**

# From quarks to matter

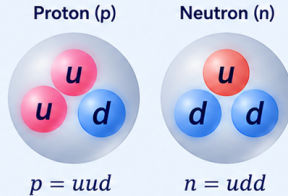
Quarks are the fundamental constituents of hadrons. Protons and neutrons are not elementary particles, but composite systems of three quarks, bound by the strong interaction.

## Quarks



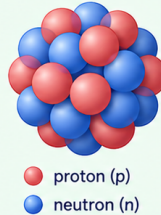
Six flavours of quarks  
(each comes in three colours)

## Protons and neutrons



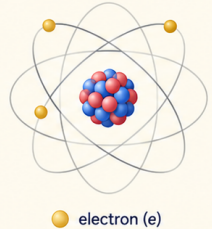
Bound states of three quarks

## Atomic nucleus



Many protons and neutrons  
bound together

## Atom



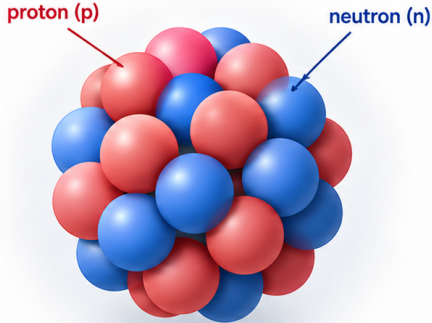
Nucleus surrounded by  
electrons

Nuclear physics begins when we ask how protons and neutrons form  
and behave as bound systems.



# The atomic nucleus

Atomic nuclei are bound systems of protons and neutrons (nucleons), held together by the strong interaction. They are at the centre of nuclear physics.



## Basic quantities

$Z$  = number of protons (atomic number)

$N$  = number of neutrons

$A = Z + N$  (mass number)

## Examples



$^{12}_6\text{C}$

$Z = 6$

$N = 6$

$A = 12$

Carbon-12



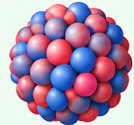
$^{16}_8\text{O}$

$Z = 8$

$N = 8$

$A = 16$

Oxygen-16



$^{238}_{92}\text{U}$

$Z = 92$

$N = 146$

$A = 238$

Uranium-238

**What holds the nucleus together?**

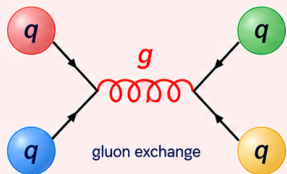
Nuclear physics explores the structure, dynamics and transformations of atomic nuclei.

# From the strong interaction to the nuclear force

The strong interaction acts between quarks, binding them inside protons and neutrons.  
The interaction between nucleons is a residual effect of the strong interaction.

## 1. Strong interaction (fundamental level)

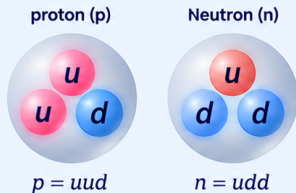
Quarks interact by exchanging gluons and carry colour charge.



**Quantum Chromodynamics (QCD)**  
SU(3) colour gauge theory

## 2. Nucleons as composite particles

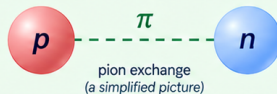
Protons and neutrons are bound states of three quarks, confined by the strong interaction.



Protons and neutrons are not elementary particles, but composite systems.

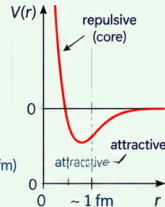
## 3. The nuclear force (nucleon level)

The interaction between nucleons is a residual effect of the strong interaction, mediated mainly by the exchange of mesons (e.g. pions).



### Properties of the nuclear force:

- Attractive at typical nuclear distances ( $\sim 1$  fm)
- Very short range
- Strongly repulsive at very short distances
- Charge independent (approximately)
- Much weaker than the strong interaction between quarks



**Nuclear physics is the physics of composite nucleons and their collective behaviour, not simply QCD at a smaller scale.**

# From elementary particles to nuclear physics

Nuclear physics studies the properties and interactions of atomic nuclei, which emerge from the fundamental particles and their interactions.

## Elementary particles



quarks



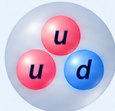
leptons



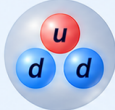
force carriers

Fundamental building blocks and interactions

## Nucleons



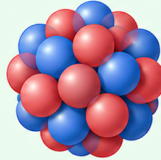
proton (p)



neutron (n)

Bound states of three quarks, held by the strong interaction

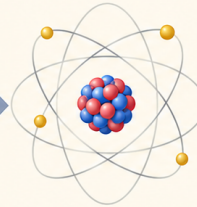
## Atomic nucleus



$Z$  protons  
 $N$  neutrons  
 $A = Z + N$

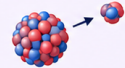
Bound system of nucleons, held by the nuclear force

## Atom



Nucleus surrounded by electrons

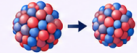
## Nuclear phenomena



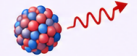
Radioactive decay



Nuclear fusion



Nuclear fission



Nuclear reactions

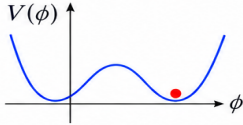
Nuclear physics connects the fundamental world of quarks and gluons to the structure and dynamics of atomic nuclei.

# What do I do?

Explore fundamental questions in Particle Physics and the Universe.

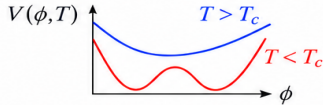
## Higgs sector

Properties of the Higgs boson and extensions of the scalar sector.



## Phase transitions

Vacuum evolution in the early Universe and cosmological consequences.



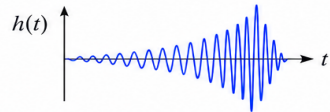
## Dark matter

The nature of dark matter and its interactions.



## Gravitational waves

Messengers from the extreme Universes.



**Physics  
beyond the  
Standard Model**

**Confront ideas with data**  
and contribute to answer  
fundamental questions.

**To understand the laws of Nature  
from the smallest to the largest scales.**