Universidad de los Andes

Departamento de Física

Nuclear Astrophysics

Neelima G. Kelkar

Nombre del curso: Nuclear Astrophysics
Código del curso: FISI 3904 (4 cred.); FISI 4904 (4 cred.)
Unidad académica: Departamento de Física
Periodo académico: 202010
Horario: Ma y Ju, 15:30 - 16:50
Salón:
Requisito: Quantum Mechanics I

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Horario y lugar de atención: IP-403, en cualquier momento.

I Introduction

Contemplating on the complexity of the world surrounding us, we could be tempted to trace back its origin to the different chemical properties of the many elements in general and as far as living beings are concerned, to the marvellous chemistry of carbon. However, a closer look reveals that these properties are emergent ones and the fundamental requirement which allows the existence of about 100 elements is the formation of nuclei heavier than the proton. Without the synthesis of heavy nuclei from protons and neutrons, atoms other than hydrogen would not exist. Therefore, the question of how exactly these heavy nuclei are synthesised in stars is of utmost interest to all of us.

Once one starts investigating the origin of elements, interesting questions arise. To list just a couple of them: the product of helium burning is ^{12}C. The triple alpha (^{4}He) reaction where 3 alphas interact directly has very low probability. However, carbon is abundant and as Fred Hoyle proposed (and was verified experimentally later), this happens since the reactions proceed through resonance formation. Why does the sun burn so slowly? It has been burning for 4.6 billion years and still goes on. The answer lies in the small probabilities (cross sections) of the thermonuclear reactions. The synthesis in stars not only provides us with all the energy we consume (be it through the daily flux of sunlight or fossil energy in the form of petroleum) but it also supplies us with all necessary elements.

The course begins with an introduction to basic knowledge and concepts in nuclear astrophysics. We will then look into some aspects of nuclear physics and the theoretical frameworks essential for understanding the processes taking place in the stellar environment. This will be followed by an overview of the different types of processes occurring in stars and their relevance for nucleosynthesis.

II Objectives

The main objectives of the course are:

- To develop an understanding for the basic nuclear physics concepts involved in the study of nuclear reactions and decays in stellar environments and their relevance for nucleosynthesis of elements.
- To develop the essential background for starting a theoretical research project in nuclear astrophysics.

III Skills developed

On completion of the course, the student is expected:

- to develop a background on the basics concepts in nuclear physics

- to be able to handle small calculations of nuclear reactions rates in stars
- to have an overview of the various processes of relevance in nuclear astrophysics

IV Weekly syllabus

The following topics will be covered during the semester (16 weeks).

- Week 1 and 2: Primer on nuclear astrophysics
  Evolution of the universe: chronologically occurring stages of different syntheses (baryogenesis, early nucleosynthesis, synthesis of heavy and super heavy elements), modeling stellar structure,
  what are abundances? Hertzsprung-Russel diagram and related physics

- Week 3: Basic ideas in Nuclear Physics
  Size of the nucleus, masses and binding energies of nuclei, magic numbers etc.

- Week 4, 5 and 6: Scattering theory and resonances in scattering
  (i) Cross sections, potential scattering and the method of partial waves,
  (ii) Resonances of nuclei and particles, their characterization and the Breit Wigner formula

- Week 7, 8 and 9: Modes of nuclear decay and nuclear decays in stars
  (i) Electromagnetic decays of nuclei
  (ii) Beta decay probabilities
  (ii) Nuclear decay through nucleon and alpha particle emission - problems treated as tunneling through the Coulomb barrier

- Week 10, 11 and 12: Stars as thermonuclear reactors
  Nuclear reactions generate the energy which makes the stars shine.
  Thermonuclear reactions:
  (i) Reaction rates of resonant and non-resonant reactions
  (ii) Broad resonance reactions (the partial widths are treated to be energy dependent here, the formalism gets involved due to this fact)
  (iii) Electron screening

- Week 13, 14 and 15: Nucleosynthesis at different stages and processes
  (i) Hydrogen, deuterium and helium burning, the triple alpha reaction, helium flash
  (ii) a short coverage of carbon, oxygen, silicon burning and nucleosynthesis beyond iron
  (iii) r- process, p-process, s-process, rp-process and their relevance to the physics of neutron rich nuclei

- Week 16: Term paper presentations

V Methodology

Since the present course is a theoretical course, the methodology involves teaching on the black board with a regular interaction with students. As mentioned below, the students will choose a topic to write a term paper and hence it will sometimes involve outside the classroom discussions with the students on topics related to the course.

VI Grades and evaluation criteria

There will be two partial exams during the semester. The students also have to present a term paper. The term paper consists of an article written by the student on a topic closely connected with the syllabus of this course. The student is expected to choose a topic and then find relevant information in books and literature and some research articles (can also be from journals with pedagogic articles) which discuss the issue. Having chosen the topic, the student can discuss the topic outside lecture hours with the lecturer if he/she finds it necessary. Based on this, he/she should be able to make a write-up on the topic and present a short talk on the same to fellow students.
Partial exams: 50 %
Term Paper: 20 % (to be submitted at the beginning of week 16),
Presentation of term paper: 5 %
Final Exam: 25 %

VII Bibliography

The topics given in the syllabus above can be found in the following books.
Main references:

1 *Nuclear Physics of Stars*, Christian Iliadis

2 *Cauldrons in the Cosmos: Nuclear Astrophysics*, C. E. Rolfs and W. S. Rodney

Additional references:

3 *Supernovae and Nucleosynthesis (Princeton Series in Astrophysics)*, David Arnett

4 *An Introduction to Nuclear Astrophysics*, Richard N. Boyd

5 *Principles of Stellar Evolution and Nucleosynthesis*, Donal D. Clayton

6 *Scattering theory : the quantum theory of non-relativistic collisions*, J. R. Taylor

7 *Nuclei and Particles*, Emilio Segre

8 *An Introduction to Modern Astrophysics*, B. W. Carroll and D. A. Ostlie

9 *Fundamentals in Nuclear Physics: From Nuclear Structure to Cosmology*, J-L. Basdevant, J. Rich and M. Spiro