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Review

LUNA: Status and prospects

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ABSTRACT

The essential ingredients of nuclear astrophysics are the thermonuclear reactions which shape the life and death of stars and which are responsible for the synthesis of the chemical elements in the Universe. Deep underground in the Gran Sasso Laboratory the cross sections of the key reactions responsible for the hydrogen burning in stars have been measured with two accelerators of 50 and 400 kV voltage right down to the energies of astrophysical interest. As a matter of fact, the main advantage of the underground laboratory is the reduction of the background. Such a reduction has allowed, for the first time, to measure relevant cross sections at the Gamow energy. The qualifying features of underground nuclear astrophysics are exhaustively reviewed before discussing the current LUNA program which is mainly devoted to the study of the Big-Bang nucleosynthesis and of the synthesis of the light elements in AGB stars and classical novae. The main results obtained during the study of reactions relevant to the Sun are also reviewed and their influence on our understanding of the properties of the neutrino, of the Sun and of the Universe itself is discussed. Finally, the future of LUNA during the next decade is outlined. It will be mainly focused on the study of the nuclear burning stages after hydrogen burning: helium and carbon burning. All this will be accomplished thanks to a new 3.5 MV accelerator able to deliver high current beams of proton, helium and carbon which will start running under Gran Sasso in 2019. In particular, we will discuss the first phase of the scientific case of the 3.5 MV accelerator focused on the study of $^{12}C+^{12}C$ and of the two reactions which generate free neutrons inside stars: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$.

Contents

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1. Introduction

Gravity triggers the birth of a star but the loss of gravitational energy alone is not enough to supply the energy radiated away during the entire lifetime of a star (Fig. 1). A different and fundamental source of energy must necessarily be assumed [1]. This source is given by the binding energy of atomic nuclei, which can be released in particular when converting protons (zero binding energy) up to medium-mass nuclei such as ^{56}Fe (binding energy per nucleon $E_B/A = 8.6$ MeV). In order to properly understand stellar structure and evolution, it is thus necessary to understand how light nuclei are converted to heavier ones: It is necessary to study nuclear reactions.

In addition to energy production and its effects on stellar structure and evolution, nuclear reactions also affect the production of neutrinos in stars. Our Sun is an example of a star with a well-studied neutrino spectrum [2,3]. Finally, nuclear reactions in stars synthesize chemical elements. All but the lightest five elements (hydrogen to boron) are predominantly produced in stars [4], and for example the crucial ratio of carbon to oxygen abundances is controlled by stellar helium burning.

The key point of a nuclear reaction is the value of its cross section at the energy at which the reaction takes place. The extremely low value of the cross section at the stellar energies, ranging from pico to femto-barn and even below, has always prevented its measurement in a laboratory at the Earth's surface, where the signal to background ratio is too small mainly because of cosmic ray interactions. Instead, the observed energy dependence of the cross-section at high energies is extrapolated to the low energy region, leading to substantial uncertainties. In particular, the reaction mechanism might change, or there might be the contribution of narrow or of large sub-threshold resonances which cannot be accounted for by the extrapolation, but which could completely dominate the reaction rate at the stellar energies.

In order to explore the low energy domain of nuclear astrophysics LUNA (Laboratory for Underground Nuclear Astrophysics) started its activity in 1991 as a pilot project with a 50 kV electrostatic accelerator [5] installed inside the laboratory under Gran Sasso (Fig. 2).

LUNA still remains the only experiment in the world running an accelerator deep underground (at the moment a 400 kV accelerator producing hydrogen and helium beams [6], LUNA 400) but its achievements have triggered two similar facilities which are now going to start in the Republic of China [7] and in the United States [8]. A project for nuclear astrophysics is also active at the Canfranc Laboratory in Spain [9]. As a matter of fact, the extremely low laboratory background under Gran Sasso has allowed for the first time nuclear physics experiments with very small count rates, down to a couple of events per month. This way, the important reactions responsible for the hydrogen burning in the Sun could be studied down to the relevant stellar energies.

At the end of the solar phase, i.e. study of reactions relevant to the Sun, LUNA started a rich program devoted to the study of the Big Bang Nucleosynthesis (BBN) and of the synthesis of the elements through the CNO, Ne–Na and Mg–Al cycles. The motivation here is to reproduce the abundance of the light elements and to identify the production site in stellar scenarios different from the Sun: hydrogen burning at the higher energies corresponding to the hydrogen shell of Asymptotic Giant Branch (AGB) stars or to the explosive phase of classical novae.

Finally, time has now come to face the next steps beyond hydrogen burning: helium and carbon burning. Their study will be performed with the new 3.5 MV single-ended accelerator which is going to be installed in Gran Sasso in 2018: LUNA MV [10,11]. The accelerator will provide hydrogen, helium and carbon (also double ionized) beams and it will be devoted to the study of those key reactions of the helium and carbon burning which are determining and shaping both the evolution of massive stars towards their final fate and the synthesis of most of the elements in the Universe.

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