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The LUNA Project: Status and First Results

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Abstract. LUNA is a pilot project initially focused on the $^3He(^3He,2p)^4He$ cross section measurement within the thermal energy region of the Sun (15-27 KeV). A compact high current 50 KV ion accelerator facility including a windowless gas target system, a beam calorimeter and four detector telescopes has been built, tested and installed underground at the Laboratori Nazionali del Gran Sasso. The sensitivity has been improved by more than four orders of magnitude, as compared to the previous experiment.
In particular, thanks to the cosmic ray suppression, we could attain a background level of less than 1 event per week, a rate similar to the one expected from $^3He(^3He,2p)^4He$ at the lower edge of the Sun thermal energy region.

1. INTRODUCTION

LUNA (Laboratory for Underground Nuclear Astrophysics) is a pilot project which has the purpose of measuring a few cross sections of the reactions which are important for the generation of energy and for the synthesis of elements in the stars.

These processes occur in the stars at energies which are far below the Coulomb barrier. In this region the cross section $\sigma(E)$ drops nearly esponentially with decreasing energy and its measurement becomes increasingly difficult. Indeed, it was not yet possible to measure $\sigma(E)$ within the thermal energy region in the stars. Instead, the observed energy dependence of $\sigma(E)$ at high energies had to be extrapolated to thermal energies, leading to substantial uncertainties. In particular, a possible resonance in the unmeasured region is not accounted for by the extrapolation, but it can completely dominate the reaction rate for low stellar temperatures. It is therefore compelling to extend the measurements in the low energy region.

This gives the possibility to study an additional effect: the electron screening. The beam and the target used in an experiment are usually made of ions and neutral atoms, respectively. The electron clouds surrounding the interacting nuclides act as a screening potential, thus reducing the height of the Coulomb barrier and enhancing the cross section. The screening effect has to be measured and taken into account in order to derive the cross section for bare nuclei, which is the starting point for nuclear astrophysics calculations.

The LUNA project is initially focused on the $^3He(^3He,2p)^4He$ cross section measurement within the thermal energy region of the Sun (15-27 KeV).

A resonance in this region has been suggested [Fowler 1972] [Fetysov and Kopysov 1972] to explain the observed high energy solar neutrino flux, a factor between 2 and 3 lower than the expected one. The enhancement in the $^3He(^3He,2p)^4He$ cross section would decrease the relative contribution of the alternative reaction $^3He(\alpha,\gamma)^7Be$, which generates the branch responsible for high energy neutrino production in the Sun.

A resonance at energy far below 100 KeV has been recently suggested [Straniero 1994] to explain the galactic abundance of ^3He. It is known [Reeves et al. 1973] that big-bang nucleosynthesis alone generates enough ^3He to account for the observations. The ^3He production by the stars is not required: the resonance in the $^3He(^3He,2p)^4He$ cross section could provide the mechanism through which the produced ^3He is also destroyed inside the star.

2. THE EXPERIMENTAL SETUP

The $^3He(^3He,2p)^4He$ cross section has been measured down to the centre of mass energy of 24.5 KeV [Krauss et al. 1987], where it has the value of 7±2 *pbarn*. This point is just at the upper edge of the thermal energy region of the Sun.

In order to measure at lower energy, where the cross section is getting smaller and smaller, it is necessary to make several improvements. In particular the accelerator has to deliver a high intensity beam even at low energy, where the space charge repulsion within the beam ions is a severe problem; the detector efficiency has to be reasonably high and the background has to be minimized.

The 50 KV LUNA accelerator setup (fig. 1) consists of a duoplasmatron ion source, a beam extraction-acceleration system and a double focusing analyzing magnet. The energy spread of the source is less than 20 eV and the acceleration voltage is know with an accuracy better than 10^{-4}.

The $^3He^+$ beam selected by the magnet enters the windowless gas target system and can interact in the detector chamber, inside which a constant ^3He pressure of 0.5 *mbar* is kept. The $^3He^+$ current entering the detector chamber is of $\sim$0.5 mA. Finally the beam is stopped in a calorimeter where, from the heat deposition, the beam intensity is derived with a 3% accuracy.

The detector setup consists of four $\Delta E - E$ silicon telescopes placed around the beam axis at the distance of 2.5 and 3.5 cm. Each detector is a square of 5 cm side and 140 μm thick (ΔE detector) and 1 mm thick (E detector).

A mylar foil and an Al foil (each of 1.5 μm thickness) are placed in front of each telescope to shield the detectors from intense elastic scattering yields as well as from beam induced light and heat. Moreover the detectors are cooled down to -20 °C in order to have a small leakage current and to mantain a good energy resolution.

With this setup, which has a ~13% detection efficiency, we can distinguish a proton from an α and measure their energy. Thanks to this possibility one can suppress the background reactions $d(^3He,p)^4He$ and $^3He(d,p)^4He$, which were one of the most severe problems in previous investigations. The deuterium is contained either in the target or in the beam, as a molecule of HD^+. Because of the lower Coulomb barrier, even a tiny deuterium contamination is enough to produce a higher rate than the one of $^3He(^3He,2p)^4He$. However the protons coming out from the two different reactions have different energies: 14.7 MeV in $d+^3He$ and less than 10.7 MeV in $^3He+^3He$. Therefore, by measuring the proton energy it is possible to distinguish between the two processes.

In addition to the background due to deuterium contamination we have to consider the background due to the natural radioactivity of the detector itself and of the environment, to the cosmic rays and to the neutrons.

A passive shielding around the detectors can provide a reduction of gammas and neutrons from the environment, but it produces at the same time an increase of gammas and neutrons due to the cosmic ray interactions in the shielding itself. An active shielding can only partially reduce the problem, because some of the activation due to spallation or μ^- capture gives rise to a delayed background.

The best solution is to strongly suppress the cosmic ray flux by going underground. At the end of 1993 we installed our accelerator facility at the Laboratori Nazionali del Gran Sasso (LNGS), at a depth equivalent to $\sim$ 3600 meters of water. Here the muon flux is reduced by a factor 10^6 and the neutron flux by a factor 10^3. LUNA is in a dedicated room separated from the other experiments by at least 60 m of rock.

The background due to the natural radioactivity of the detector setup itself is suppressed by the coincidence requirement between the proton signals in the ΔE and E detectors of a telescope.

3. STATUS AND FIRST RESULTS

The 50 KV facility has been tested over a period of 3 months at the Bochum University and then moved to LNGS in late 1993.

During the test phase it was possible to obtain some interesting physics results. In particular we measured the $d(^3He,p)^4He$ cross section down to the centre of mass energy of 5.4 KeV, where we clearly saw the enhancement due to the electron screening. Of course we will repeat and improve the experiment underground, thus exploiting the strong background reduction. In particular we will measure in the lower energy region, where the screening effect is getting larger and larger and its determination is less dependent on the extrapolation from the high energy data. However the results already show the LUNA capability of performing cross section measurements at energies far below those of previous works.

Our facility can be easily connected to an accelerator of higher energy. We did so with the 450 KV Bochum accelerator and we measured the $^3He(^3He,2p)^4He$ cross section over the centre of mass energy region from 46 to 92 KeV. The results are in good agreement with the existing measurement [Krauss et al. 1987] both in the energy dependence as well as in the absolute scale.

We also verified that the $^3He(^3He,2p)^4He$ protons can be easily separated from the protons due to $d(^3He,p)^4He$ or $^3He(d,p)^4He$.

The LUNA facility is now installed underground at LNGS, where, first of all, we checked the background reduction. Background events are all the proton-like events in the energy region of the $^3He(^3He,2p)^4He$ protons. We counted less than 1 of them per week , with at least a factor 200 reduction as compared to the background we measured in Bochum.

We are now starting the measurement of the $^3He(^3He,2p)^4He$ cross section. First at the centre of mass energy of 25 KeV, an important point for the overlap with the previous work [Krauss et al. 1987], and where we expect the "huge" rate of ~130 events per day. We will then decrease the energy to cover the thermal energy region of the Sun, thus approaching the low rate typical of many underground experiments: for instance ~2 events per week at the centre of mass energy of 17 KeV (this rate has been calculated without taking into account the screening effect and a possible resonance).

4. CONCLUSION

LUNA is a pilot project initially focused on the $^3He(^3He,2p)^4He$ cross section measurement within the thermal energy region of the Sun.

To achieve this goal the experimental sensitivity has been improved, as compared to the previous experiment, by more than four orders of magnitude: a factor 3 in the beam current, a factor 20 in the detection efficiency and more than a factor 200 in the background reduction.

We are now starting the experiment with the 50 KV accelerator facility installed underground at LNGS.

The $^3He(^3He,2p)^4He$ cross section measurement will last for about one year, after which, we hope, LUNA will have shown that it is possible to explore new interesting regions in nuclear astrophysics by going underground and by using some of the typical techniques of underground physics.

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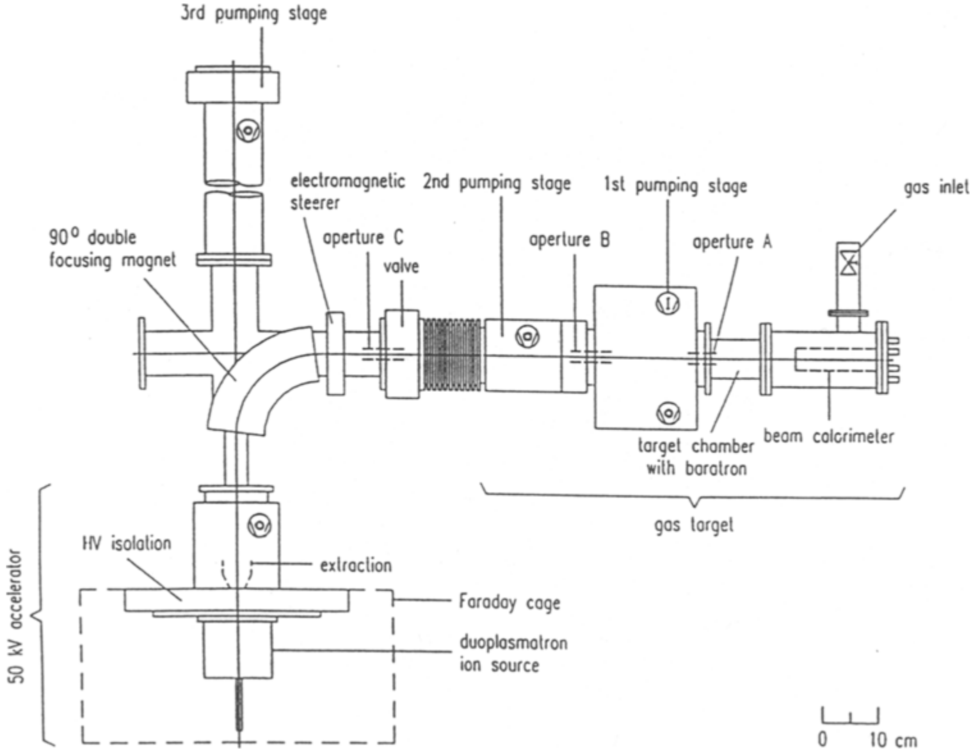

Fig. 1.— Schematic diagram of the 50 KV LUNA facility.