First Measurement of the $^3\text{He} (^3\text{He}, 2p)^4\text{He}$ Cross Section down to the Lower Edge of the Solar Gamow Peak

THE LUNA COLLABORATION

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We give the LUNA results on the $\sigma(E)$ cross section measurement of a key reaction of the proton-proton chain strongly affecting the calculated neutrino luminosity from the Sun: $^3\text{He} (^3\text{He}, 2p)^4\text{He}$. Due to the cosmic ray suppression provided by the Gran Sasso underground laboratory it has been possible to measure $\sigma(E)$ down to the lower edge of the solar Gamow peak, i.e. as low as 16.5 keV centre of mass energy. The data clearly show the cross section increase due to the electron screening effect but they do not exhibit any evidence for a narrow resonance suggested to explain the observed solar neutrino flux.

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The nuclear reactions which generate the energy of stars and, in doing so, synthesize elements occur inside stars at energies within the Gamow peak: $E_0 = E_0 \pm \delta E_0$. In this region, which is far below the Coulomb energy $E_c$ (approximately $E_0/E_c = 0.01$), the reaction cross section $\sigma(E)$ drops nearly exponentially with decreasing energy $E$ (1):

$$\sigma(E) = \frac{S(E)}{E} \exp(-2 \pi \eta), \quad (1)$$

where $S(E)$ is the astrophysical factor and $\eta$ is the Sommerfeld parameter, given by $2 \pi \eta = 31.29 Z_1 Z_2 (\mu/E)^{1/2}$. $Z_1$ and $Z_2$ are the nuclear charges of the interacting particles in the entrance channel, $\mu$ is the reduced mass (in units of amu), and $E$ is the center of mass energy (in units of keV).

The extremely low value of $\sigma(E)$ within the Gamow peak has always prevented its measurement in a laboratory at the Earth surface. As a matter of fact, the signal to background ratio would be too small because of the cosmic ray interactions. Instead, the observed energy dependence of $\sigma(E)$ at high energies is extrapolated to the low energy region, leading to substantial uncertainties. In particular, a possible resonance in the unmeasured region is not accounted for by the extrapolation, but it could completely dominate the reaction rate at the Gamow peak.

In addition another effect can be studied at low energies: the electron screening. The beam and the target used in an experiment are usually ions and neutral atoms, respectively. The electron clouds surrounding the interacting nuclei act as a screening potential, thus reducing the height of the Coulomb barrier and leading to a higher cross section, $\sigma_s(E)$, than would be the case for bare nuclei, $\sigma_b(E)$, with an exponential enhancement factor (2): $f_{\text{lab}}(E) = \sigma_s(E)/\sigma_b(E) \simeq \exp(\pi \eta U_c/E)$, where $U_c$ is the electron-screening potential energy. It should be pointed out that the screening effect has to be measured and taken into account to derive the bare nuclei cross section, which is the input data to the models of stellar nucleosynthesis.

Therefore both the search for narrow resonances and the study of electron screening demand for the direct measurement of the nucleosynthesis cross sections in the low energy region (few tens of keV). In order to start exploring this new and fascinating domain of nuclear astrophysics we installed an accelerator facility deeply underground where the cosmic rays, which are the limiting background in all the existing experiments, are strongly suppressed.

LUNA [2] (Laboratory for Underground Nuclear Astrophysics) is located in a dedicated room of the Laboratori Nazionali del Gran Sasso (LNGS), separated from other experiments by at least 60 m of rock. The mountain provides a natural shielding equivalent to at least...
3800 meters of water which reduces the muon and neutron fluxes by a factor $10^6$ and $10^7$, respectively. The $\gamma$ ray flux is like the surface one, but a detector can be more effectively shielded underground due to the suppression of the cosmic ray induced background.

Technical details of the LUNA set-up have already been reported. Briefly, the 50 kV accelerator facility consists of a duoplasmatron ion source, an extraction/acceleration system, a double-focusing 90° analysing magnet, a windowless gas-target system and a beam calorimeter. Its outstanding features are the following: very small beam energy spread (the source spread is less than 20 eV, acceleration voltage known with an accuracy of better than $10^{-4}$), and high beam current even at low energy (about 300 $\mu$A measurable with a 3% accuracy).

Since the beginning LUNA has been focused on the $^3He(^3He,2p)^4He$ cross section measurement within the solar Gamow peak (15-27 keV). This reaction plays a big role in the proton-proton chain, strongly affecting the calculated solar neutrino luminosity. As a matter of fact a resonance at the thermal energy of the Sun has been suggested long time ago to explain the observed solar neutrino flux, which is a factor between 2 and 3 lower than expected. The possible resonant 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 $^7Be$ and $^8B$ neutrino production in the Sun.

A resonance at an energy far below 100 keV has also been discussed to explain the galactic abundance of $^3He$. It is known that big-bang nucleosynthesis alone generates enough $^3He$ to account for the observations. The $^3He$ production by stars is not required: the resonance in the $^3He(^3He,2p)^4He$ cross section could provide a mechanism through which the produced $^3He$ is destroyed inside stars.

Before LUNA the $^3He(^3He,2p)^4He$ cross section measurements stopped at the centre of mass energy of 24.5 keV ($\sigma=7\pm 2 pb$), just at the upper edge of the thermal energy region of the Sun. In the underground experiment we measured for the first time down to 20.76 keV and then, with a different detector set-up, down to 16.5 keV.

The first detector set-up consisted of four $\Delta E$-E telescopes placed around the beam axis. Each telescope was made of a thin (140 $\mu$m) transmission surface barrier silicon detector followed by a thick one (1 mm), both of 5x5 cm$^2$ area. The signature of a $^3He(^3He,2p)^4He$ event was a proton signal within a fixed energy window in one and only one telescope.

With this set-up we collected data until August 1996 down to the centre of mass energy of 20.76 keV, with no evidence of the hypothetical resonance. At the lowest energy we had a rate of 3 events/day, giving a cross section $\sigma=0.9\pm 0.1 pb$.

We could not go further down because of the background reaction $^3He(d,p)^4He$, which at low energies has a cross section much larger than that of $^3He(^3He,2p)^4He$ (deuterium is contained in the $^3He^+$ beam as HD$^+$ molecule): for instance, at 16.5 keV centre of mass energy it is larger by eight orders of magnitude.

The 14.9 MeV protons from $^3He(d,p)^4He$ have an energy larger than the protons from $^3He(^3He,2p)^4He$ (a continuous spectrum up to 10.7 MeV), however a few of them can hit the detectors near the edges of their active volumes loosing only a fraction of their energy and thus giving the same signature as the $^3He(^3He,2p)^4He$ events.

In order to suppress this background we had to use a new detector set-up, which consists of eight thick (1 mm) silicon detectors of 5x5 cm$^2$ area placed around the beam. They form a 12 cm long parallelepiped in the target chamber, at 5.3 cm from its entrance. Each detector is cooled down to -20°C, to reduce the leakage current, and it is shielded by a 1 $\mu$m thick Mylar foil, a 1 $\mu$m aluminium foil and a 10 $\mu$m nickel cylinder in order to stop the produced $^3He$ nuclei, the elastically scattered $^3He$ and the light induced by the beam.

Standard NIM electronics is reading out the detectors. The signals are then handled and stored using a CAMAC multiparametric system which also stores information on the experimental parameters and on the count rate of the pulser used for dead time and electronic stability checks.

Inside the chamber, which has a length of 41.9 cm, there is a constant $^3He$ gas pressure of 0.5 mbar (measured to an accuracy of better than 1%). In going through the gas, the beam experiences a mean energy loss of about 3 keV (1 keV to the middle of the detector set-up). This is taken into account by introducing an effective beam energy $E_{eff}$ corresponding to the mean value of the beam energy distribution in the detector set-up, evaluated by Monte Carlo simulation for each different accelerating voltage. Since at subcoulomb energies a precise knowledge of the effective beam energy is crucial, all the Monte Carlo predictions have been thoroughly tested by changing the target gas pressure and the detector position.

In the data analysis we want to select those events where two protons are detected. As a matter of fact this is the signature which unambiguously identifies a $^3He(^3He,2p)^4He$ fusion reaction, thus completely suppressing the background events due to $^3He(d,p)^4He$ where only one proton is emitted. It was not possible to ask for such a signature in the old set-up because the detection efficiency would have been too low (less than 1%).

Therefore selected events must fulfill the following conditions:

1. there is a coincidence, within 1 $\mu$s, between the signals of two silicon detectors; this essentially elim-
inates the events due to the natural radioactivity of the detectors themselves and of the surrounding materials;

2. each proton deposits more than 2 $MeV$ in the detector and the sum of the two proton energies is within the constraints given by the Q-value (12.86 $MeV$) of the reaction, thus cutting away the electronic noise;

3. the coincidence occurs between two and only two detectors; in this way events which trigger more than two detectors are rejected in order to remove the residual electronic noise and the muon induced showers.

These requirements lead to an absolute detection efficiency of $5.3\pm 0.2\%$ as determined by the Monte Carlo program \[1\]. No event has been detected fulfilling our selection criteria during a 23 day background run with a $^3He$ beam (297 $C$) on a $^3He$ target (0.5 $mbar$).

In Table I we give the new results which conclude the LUNA measurement of the $^3He(3He,2p)^4He$ cross section. We point out that the cross section varies by more than two orders of magnitude in the measured energy range. At the lowest energy of 16.5 $keV$ it has the value of $0.02\pm 0.02 \, pb$, which corresponds to a rate of about 2 events/month, rather low even for the ‘silent’ experiments of underground physics.

The astrophysical factor $S(E)$ is also shown in Fig. 1, together with the values we obtained underground with the four telescope set-up: there is an excellent agreement between the two different detector set-ups in the overlapping region.

The dominant error on the new data is the statistical one, with the systematical error mainly arising from the 10% uncertainty in the beam energy loss inside the target.

In Fig. 2 we plot two existing measurements [8] [12] of the astrophysical factor $S(E)$ together with our underground and surface [10] results. By fitting the observed energy dependence of $S(E)$ from 16.5 $keV$ to 1080 $keV$ with the expressions:

\[
S_b(E) = S_b(0) + S_b'(0)E + 0.5 S_b''(0)E^2 \quad (3)
\]
\[
S_s(E) = S_b(E) \exp(\pi\eta U_e/E) \quad (4)
\]

we obtain the values of the parameters $S_b(0)$, $S_b'(0)$, $S_b''(0)$ and $U_e$ given in Table II ($S_b$ and $S_s$ are the astrophysical factors for bare and shielded nuclei, respectively).

We observe that these values are in excellent agreement with our previous results [10] and that the screening potential (294\pm 47 $eV$) is close to the one from the adiabatic limit (240 $eV$).

From our measurement it is concluded that the $^3He(3He,2p)^4He$ cross section increases at the thermal energy of the Sun as expected from the electron screening effect but does not show any evidence for a narrow resonance. Consequently, the astrophysical solution of the solar neutrino problem based on its existence is ruled out by our results.

In conclusion, LUNA has provided the first cross section measurement of a key reaction of the proton-proton chain at the thermal energy of the Sun. In this way it has also shown that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars.

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FIG. 1. The $^3\text{He}(^3\text{He}, 2p)^4\text{He}$ astrophysical factor $S(E)$ measured underground with the LUNA old set-up (four telescopes) and with the new one (eight thick silicon detectors). The error bars correspond to one standard deviation.

FIG. 2. The $^3\text{He}(^3\text{He}, 2p)^4\text{He}$ astrophysical factor $S(E)$ from two previous measurements and from LUNA (underground + surface). The lines are the fit to the astrophysical factors of bare and shielded nuclei. The solar Gamow peak is shown in arbitrary units.
### TABLE I. The LUNA results with the new detector set-up.

| Energy (keV) | Charge (C) | Events | S(E) (MeV b) | ΔS_{\text{stat}} (MeV b) | ΔS_{\text{sys}} (MeV b) |
|-------------|------------|--------|--------------|--------------------------|-------------------------|
| 16.50       | 349        | 1      | 7.70         | 7.70                     | 0.49                    |
| 16.99       | 827        | 7      | 13.15        | 4.98                     | 0.83                    |
| 17.46       | 189        | 1      | 5.26         | 5.26                     | 0.33                    |
| 17.97       | 272        | <14    |              |                          |                         |
| 18.46       | 337        | 7      | 7.86         | 2.97                     | 0.47                    |
| 18.98       | 387        | 13     | 8.25         | 2.29                     | 0.48                    |
| 19.46       | 242        | 12     | 7.67         | 2.22                     | 0.44                    |
| 19.93       | 190        | 9      | 5.10         | 1.70                     | 0.29                    |
| 21.43       | 365        | 53     | 4.72         | 0.65                     | 0.26                    |
| 23.37       | 167        | 141    | 7.31         | 0.63                     | 0.39                    |
| 24.36       | 298        | 278    | 5.44         | 0.34                     | 0.28                    |

*Effective center of mass energy derived from the absolute energy of the ion beam and the Monte Carlo simulation (including the energy loss of the beam inside the target gas and the effects of the extended gas-target and detector geometries).*

*Deducted from the beam calorimeter.*

*The upper limit at 17.97 keV energy is given at the 95 % confidence level.*

*Statistical error (one standard deviation).*

*Systematical error (one standard deviation).*

### TABLE II. The $S_b(E)$ factors and the electron screening potential energy $U_e$ given by the fit to the data shown in Fig. 2.

| $S_b(0)$ (MeV b) | $S'_b(0)$ (b) | $S''_b(0)$ (b/MeV) | $U_e$ (eV) | $\chi^2/d.o.f.$ |
|-----------------|--------------|-------------------|-------------|-----------------|
| 5.32 ± 0.08     | -3.7 ± 0.6   | 3.9 ± 1.0         | 294 ± 47    | 0.86            |
LUNA
Dwarakanath and Winkler (1971)
Krauss et al. (1987)

LUNA

Dwarakanath and Winkler (1971)

Krauss et al. (1987)

Gamow peak

$S \ [\text{MeV b}]$

$E_{\text{CM}} \ [\text{keV}]$

bare nuclei

shielded nuclei