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

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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: $^3He(^3He, 2p)^4He$. Because of the cosmic ray suppression provided by the Gran Sasso underground laboratory, it has been possible to measure $\sigma(E)$ throughout the energy range in which this reaction occurs in the Sun, i.e., down to 16.5 keV center 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 ^8B and ^7Be solar neutrino flux reduction. [S0031-9007(99)09440-5]

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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: $E_0 \pm \delta E_0$. 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 η 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, μ 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. The signal to background ratio would be too small, even with the highest current beam, 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 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 [1],

$$f_{lab}(E) = \sigma_s(E)/\sigma_b(E) \simeq \exp(\pi\eta U_e/E), \quad (2)$$

where U_e 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 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 of the existing experiments, are strongly suppressed.

LUNA (Laboratory for Underground Nuclear Astrophysics) [2] 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 of 10^6 and 10^3, respectively. The γ ray flux is like the surface one, but a detector can

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be more effectively shielded underground due to the suppression of the cosmic ray induced background.

Technical details of the LUNA setup have already been reported [3]. Briefly, the 50 kV accelerator facility consists of a duoplasmatron ion source, an extraction/acceleration system, a double-focusing 90° analyzing 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 μA measurable with a 3% accuracy).

Since the beginning, LUNA has been focused on the ^{3}He(^{3}He, $2p$)^{4}He 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. A resonance at the thermal energy of the Sun was suggested long ago [4,5] to explain the observed ^{8}B solar neutrino flux: it would decrease the relative contribution of the alternative reaction ^{3}He(α, γ)^{7}Be, which generates the branch responsible for ^{7}Be and ^{8}B neutrino production in the Sun. A narrow resonance with a peak S factor 10–100 times the value extrapolated from high energy measurements cannot be ruled out with the existing data. Such an enhancement would be required to reduce the ^{7}Be and ^{8}B solar neutrinos by a factor of 2–3.

A resonance at an energy far below 100 keV has also been discussed [6] to explain the galactic abundance of ^{3}He. It is known [7] that big-bang nucleosynthesis alone generates enough ^{3}He to account for the observations. The ^{3}He production by stars is not required: the resonance in the ^{3}He(^{3}He, $2p$)^{4}He cross section could provide a mechanism through which the produced ^{3}He is destroyed inside stars.

Before LUNA, the ^{3}He(^{3}He, $2p$)^{4}He cross section measurements stopped at the center of mass energy of 24.5 keV ($\sigma = 7 \pm 2$ pb) [8], just at the upper edge of the thermal energy region of the Sun. Previously we reported on the underground measurements we made down to 20.76 keV [9,10]; here we present new results down to 16.5 keV using an improved detector setup.

The new detector setup consists of eight thick (1 mm) silicon detectors of 5×5 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 μm thick Mylar foil, a 1 μm aluminum foil, and a 10 μm nickel cylinder in order to stop the produced ^{4}He nuclei, the elastically scattered ^{3}He, and the light induced by the beam.

Standard electronics is reading out the detectors. The signals are then handled and stored using a 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 ^{3}He 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 setup). 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 setup, evaluated by a Monte Carlo simulation for each different accelerating voltage. Since at sub-Coulomb energies a precise knowledge of the effective beam energy is crucial, all of 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. This is the signature which unambiguosly identifies a ^{3}He(^{3}He, $2p$)^{4}He fusion reaction, thus completely suppressing the events due to ^{3}He(d, p)^{4}He which were the limiting background with the old setup (deuterium is contained in the ^{3}He$^+$ beam as HD$^+$ molecule).

Therefore selected events must fulfill the following conditions.

(1) There is a coincidence, within 1 μs, between the signals of two silicon detectors; this essentially eliminates 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

TABLE I. The LUNA results with the new detector setup.

Energy[a] (keV)	Charge[b] (C)	Events	$S(E)$[c] (MeV b)	ΔS_{stat}[d] (MeV b)	ΔS_{sys}[e] (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	0	<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

[a]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).
[b]Deduced from the beam calorimeter.
[c]The upper limit at 17.97 keV energy is given at the 95% confidence level.
[d]Statistical error (one standard deviation).
[e]Systematical error (one standard deviation).

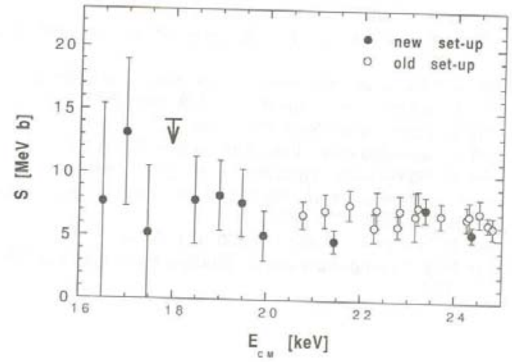

FIG. 1. The $^3He(^3He, 2p)^4He$ astrophysical factor $S(E)$ measured underground with the LUNA old setup [10] and with the new one. The error bars correspond to one standard deviation.

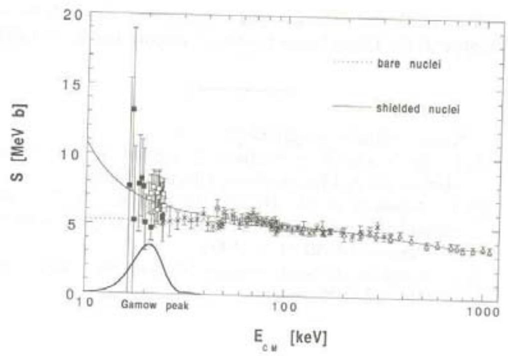

FIG. 2. The $^3He(^3He, 2p)^4He$ astrophysical factor $S(E)$ from two previous measurements and from LUNA. The results are from Dwarakanath and Winkler (triangle) [13], Krauss *et al.* (cross) [8], LUNA underground new setup (black square), LUNA old setup [10], both underground (white square) and at the surface (crossed square). The lines are the fit to the astrophysical factors of bare and shielded nuclei. The solar Gamow peak is shown in arbitrary units.

two detectors are rejected in order to remove the residual electronic noise and the muon induced showers.

These requirements lead to a detection efficiency of $(5.3 \pm 0.2)\%$ as determined by the Monte Carlo program [11]. The error comes mainly from the uncertainties on the position of the detectors and on the profile of the beam. The reliability of the Monte Carlo has been checked with the measurement of the $^3He(d, p)^4He$ cross section [12].

No event has been detected fulfilling our selection criteria during a 23-day background run with a ^4He beam (297 C) on a ^4He target (0.5 mbar).

In Table I we give the new setup 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 2 orders of magnitude in the measured energy range. At the lowest energy of 16.5 keV it has the value of 0.02 ± 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 previously obtained with the old detector setup [10]: there is an excellent agreement between the two different detector setups in the overlapping region.

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

In Fig. 2 we plot two existing measurements [8,13] of the astrophysical factor $S(E)$ together with all of the LUNA results, both the ones made with the old detector setup down to 20.76 keV [10] and the ones made at lower energies with the new setup. By fitting the observed energy dependence of $S(E)$ from 16.5 to 1080 keV with the expressions

$$S_b(E) = S_b(0) + S_b'(0)E + 0.5S_b''(0)E^2, \qquad (3)$$

$$S_s(E) = S_b(E)\exp(\pi\eta U_e/E), \qquad (4)$$

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). These values are in excellent agreement with our previous results [10], and the screening potential (294 ± 47 eV) is close to the one from the adiabatic limit (240 eV). We observe that only the high energy points of the new data give a significant contribution to determine the screening potential.

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 ^8B and ^7Be solar neutrino problem based on its existence is ruled out by our results. As a matter of fact, a 1 keV width resonance centered at 17 keV should give an astrophysical factor of 172 MeV b (459 MeV b) to suppress the ^8B and ^7Be solar neutrinos by a factor of 2 (3).

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.

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.

$S_b(0)$	$S_b'(0)$	$S_b''(0)$	U_e	χ^2/d.o.f.
5.32 ± 0.08	-3.7 ± 0.6	3.9 ± 1.0	294 ± 47	0.86

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