Solar neutrino production rate
by He reactions and atomic electron effects

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1) to reconfirm $S_{33}$-factor to prospect neutrino flux with standard solar model

2) to deduce $S(E)$ factor between 45 keV and 25 keV with less statistical and systematic errors

3) to investigate the electron screening of nuclear reactions in the laboratory
p-p chain reactions

\[ 4p \rightarrow \alpha + 2e^+ + 2\nu \quad (Q=26.46\text{MeV}) \]

\[ p + p \rightarrow d + e^+ + \nu_e \]

\[ d + p \rightarrow ^3\text{He} + \gamma \]

\[ ^3\text{He} + \alpha \rightarrow ^7\text{Be} + \gamma \]

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

- **S-factor**
  - input parameter of standard solar model
  - extrapolation from high energy region

\[ \sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta(E)) \]

\[ \phi(pp) \approx S_{11}^{0.14} S_{33}^{0.03} S_{34}^{0.06} \]

\[ \phi(7\text{Be}) \approx S_{11}^{-0.97} S_{33}^{-0.43} S_{34}^{0.86} \]

\[ \phi(8\text{B}) \approx S_{11}^{2.6} S_{33}^{-0.40} S_{34}^{0.81} S_{17}^{1.0} S_{e^-}^{-1.0} \]
Experimental Facility

$^{3}\text{He}^+ 930 \mu\text{A}$

Ion Source output: 6 mA

$\Delta E\text{-}E$ Counter Telescope

$^{3}\text{He}$ gas target

E-COUNTER
- active area: 2500 mm$^2$
- thickness: 150 $\mu$m

Mylar foil
- thickness: 20 $\mu$m

$\Delta E$-COUNTER
- active area: 2500 mm$^2$
- thickness: 140 $\mu$m
Summary of data for OCEAN

Energy range:
- 20-100 keV $^3$He$^{2+}$ 110μA
- 10-50 keV $^3$He$^{1+}$ 1mA

Ion source: NANOGUN ECR 10GHz

Charge state: 1+ and 2+, no mol. interference

Extraction: Multi-electrode (original design)

H.V. power:
- max 60 keV, ripple $< 1 \times 10^{-4}$ and stability $< 1 \times 10^{-4}$/8h, measured with precise resistor chain

Analyzer magnet: 90 double focusing, fixed entry and exit, flat and wide pole

Focusing: Q-doublet (zooming)

Simulation code: GIOS: include space charge effect

Evacuation: Differential pumping, TMP + Herical TMP

Purification: Cryo-pump + TMP + diaphragm pump

Pressure: Barocel $< 0.15\%$

Calorimeter: Heat Flux Sensors (OMEGA HFS-3)
Cross section of $^3\text{He}(^3\text{He},2p)^4\text{He}$ measured at solar energies at LUNA

<table>
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<tr>
<th>Energy (keV)</th>
<th>Charge (Cb)</th>
<th>Counts</th>
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FIG. 1. The $^3$He($^3$He, $2p$)$^4$He 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 $^3\text{He}(^3\text{He}, 2p)^4\text{He}$ 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.
Previous experimental results for $^3\text{He}(^3\text{He},2\text{p})^4\text{He}$ reaction 2002 we measured at 29.1 and 27.1 keV but the data includes severe electronic noise in the scatter plot and we withdraw these data from this figure and 2003 remeasured it.
Previous measurements of the $^3$He + $^3$He reaction by using OCEAN

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<th>$E_{cm}$ (keV)</th>
<th>Live Time (sec)</th>
<th>Beam Curr (μA)</th>
<th>Target Press. (Torr)</th>
<th>Target Tmp (°C)</th>
<th>$^3$He + $^3$H BG (Counts)</th>
<th>BG (Counts)</th>
<th>Cross Section (barn)</th>
<th>S-Factor (MeV·b)</th>
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<td>1.83×10^-9</td>
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<td>8.21×10^-2</td>
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<td>293</td>
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$^3\text{He}(^3\text{He},2p)^4\text{He}$

- Recent experiment with OCEAN
- April 2$^{nd}$ – 7$^{th}$ background measurement
- April 8$^{th}$ calibration of calorimeter
- April 10$^{th}$ - 11$^{th}$ $E_{cm}=45$ keV
- April 11$^{th}$ - 28$^{th}$ $E_{cm}=30$ keV
- April 28$^{th}$ – May 26$^{th}$ $E_{cm}=28$ keV
28 keV
Measurement in 2003 April 28~May 26
Preliminary result

- Efficiency 0.946E-01
- $^3\text{He}+^3\text{He}$ 678.1
- $^3\text{He}+\text{d}$ 33.9
- $E_{\text{cm}} = 30.$ keV
- $\sigma = 1.79(\pm 0.724) \times 10^{-10}$ barn
- $S = 6.89(\pm 0.277)$ MeV*barn
- live time 1233966 (s)
- $\langle I \rangle = 143.65.9$ (10^-6 A)
- $\langle p \rangle = 0.0752$ (Torr)
- Temp = 30.026 (度)
- $E = 30.41$ (keV)
Measurement in 2003 April 28~May 26
Preliminary result

Efficiency 0.948E-01

- $^{3}\text{He}+^{3}\text{He}$ 413.1
- $^{3}\text{He}+^{d}$ 28.8
- $E_{\text{cm}} = 28.09$ keV
- $\sigma = 7.83(\pm0.411) \times 10^{-11}$ barn

- $S = 7.99(\pm0.419)$ MeV*barn

- live time 1746821 (s)
- $\langle I \rangle = 154.9 \ (10^{-6} \ A)$
- $\langle p \rangle = 0.0688 \ (\text{Torr})$
- Temp = 30.02 (度)
- E = 28.228 (kV)
**p-p chain reactions**

**p-p chain**

\[ 4p \rightarrow \alpha + 2e^- + 2\nu \quad (Q=26.46\text{MeV}) \]

\[ p + p \rightarrow d + e^+ + \nu_e \]

**GALLEX SAGE** \( ^7\text{Ga} \)

\[ d + p \rightarrow ^3\text{He} + \gamma \]

**86%**

\[ ^3\text{He} + ^3\text{He} \rightarrow \alpha + p + p \]

\( (Q=12.86\text{ MeV}) \)

\[ \sigma_{-\text{pb}} \quad E_{cm}=17-27\text{keV} \]

- **S-factor**
  - input parameter of standard solar model
  - extrapolation from high energy region

\[ \sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta(E)) \]

**S-factor**

\[ \phi(pp) \propto S_{11}^{0.14} S_{33}^{0.03} S_{34}^{-0.06} \]

\[ \phi(\ ^7\text{Be}) \propto S_{11}^{-0.97} S_{33}^{-0.43} S_{34}^{0.86} \]

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

**7Be + p \rightarrow ^8\text{B} + \gamma**

**HOMESTAKE** \( ^{3}\text{Cl} \)

\[ ^7\text{Li} + p \rightarrow \alpha + \alpha \]

**Super Kamiokande** (water Chernkov)

\[ \alpha + \alpha \]

\[ \phi(^8\text{B}) \propto S_{11}^{-2.6} S_{33}^{-0.40} S_{34}^{0.81} S_{17}^{1.0} S_{e^-}^{-1.0} \]
Screening potential problem
Screening energies

(ref. K.Langanke and C.A.Barns, Advance of Nucl. Phys.)

<table>
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<tr>
<th>Reaction</th>
<th>$\Delta E$ (eV) experiment</th>
<th>$\Delta E$ (eV) adiabatic limit</th>
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<td>$d(^{3}\text{He}, p)^{4}\text{He}$</td>
<td>180 ± 30</td>
<td>119</td>
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<tr>
<td>$^{6}\text{Li}(p, \alpha)^{3}\text{He}$</td>
<td>470 ± 150</td>
<td>186</td>
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<tr>
<td>$^{6}\text{Li}(d, \alpha)^{4}\text{He}$</td>
<td>380 ± 250</td>
<td>186</td>
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<tr>
<td>$^{7}\text{Li}(p, \alpha)^{4}\text{He}$</td>
<td>300 ± 280</td>
<td>186</td>
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<tr>
<td>$^{11}\text{B}(p, \alpha)^{2}\text{He}$</td>
<td>620 ± 65</td>
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The screening enhancement factor for the most important astrophysical nuclear reactions of the CNO bi-cycle, $^{13}\text{C}(p,\gamma)^{14}\text{N}, E_{\text{gp}}=24.5$ keV, $^{14}\text{N}(p,\gamma)^{15}\text{O}, E_{\text{gp}}=27.2$ keV $^{16}\text{O}(p,\gamma)^{17}\text{F}, E_{\text{gp}}=29.8$ keV, solid, dashed and dotted sudden(lower) and adiabatic(upper) Phys.Rev. C 63 (2001) T.E.Liolios
The screening enhancement factor for the most important astrophysical nuclear reactions of the CNO bi-cycle, \(13C(p,\gamma)14N, E_{\gamma p}=24.5 \text{ keV}\), \(14N(p,\gamma)15O, E_{\gamma p}=27.2 \text{ keV}\), \(16O(p,\gamma)17F, E_{\gamma p}=29.8 \text{ keV}\) solid, dashed and dotted sudden(lower) and adiabatic(upper).

The Trojan horse method (THM)

- A direct measurement of bare nucleus cross section using bare beam and bare target is difficult. Needs sophisticated apparatus, NARITA as we proposed later.
- An alternative method
- Trojan horse method is applied
- \( A + x \rightarrow B + b \) data could be extracted from a suitable three-body reaction.
- \( A + a \rightarrow B + b + c(\text{spectator}) \)
- Trojan horse \( a = x + c(\text{spectator}) \)
- \( c \) is spectator retaining its momentum throughout the process.
THM(2)

- One cannot extract precisely absolute values of two body cross section but it is possible to obtain reliable information on the energy dependence of bare cross section

- It should be normalized

- From these data it can extract the value $U_e$ in a model independent way
Improved information on the $^2\text{H}(^6\text{Li},\alpha)^4\text{He}$ reaction extracted via the “Trojan horse” method

A. Musumara,$^{1,2}$ R. G. Pizzone,$^{1,2}$ S. Blagus,$^3$ M. Bogovac,$^3$ P. Figuera,$^1$ M. Lattuada,$^{1,4}$ M. Milin,$^3$ Đ. Miljančič,$^3$ M. G. Pellegriti,$^{1,2,5}$ D. Rendić,$^3$ C. Rolfs,$^6$ N. Soić,$^3$ C. Spitaleri,$^{1,2,8}$ S. Typel,$^7$ H. H. Wolter,$^8$ and M. Zadro$^3$
Improved information on the $^2\text{H}(^6\text{Li},\alpha)^4\text{He}$ reaction extracted via the “Trojan horse” method

A. Musumarra,1,2 R. G. Pizzone,1,2 S. Blagus,3 M. Bogovac,3 P. Figuera,1 M. Lattuada,1,4 M. Milin,3 Đ. Miljanić,3 M. G. Pellegriti,1,2,5 D. Rendić,3 C. Rolfs,6 N. Soić,7 C. Spitaleri,1,2,* S. Typel,7 H. H. Wolter,8 and M. Zadro3

<table>
<thead>
<tr>
<th>$S(0)$ [MeV b]</th>
<th>$S_1$ [b]</th>
<th>$S_2$ [MeV$^{-1}$b]</th>
<th>$U_e$ [eV]</th>
<th>$U^{ad}_e$ [eV]</th>
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<td>16.9±0.5</td>
<td>-41.6</td>
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<td>320±50</td>
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to investigate the electron screening of nuclear reactions in the laboratory

The systematic discrepancy between the experimental Ue value and the Ue=175 eV derived from the atomic physics theory (essentially the adiabatic approximation) is thus confirmed. Phys. Rev. C 64 068801

D(6Li,a)4He  their extracted value Ue=320 ±50 is significantly higher than the value predicted by current theoretical models
Beam - Target Experiment
Electron beam ion trap
Transverse cross section of the BeTa
Electron Beam Mode of the BeTa Operation

a) Pulse nucleus beam mode

Beam nucleus trap sections — Target nucleus trap section

Nucleus beam energy variation

Voltage on the electron beam optics elements
Electric potentials on the axis of a pure electron beam
Electric potential on the axis in cases of 100% compensation
Ground potential

Beam — target overlap

Along the axis cross sections of a nucleus beam trap, of a nucleus beam and of a nucleus target trap, in an electron beam.
Transversal cross section view of the inner region of the BeTa apparatus

- Inner 78 K terminal
- Semiconductor $\Delta E$, $E$—detectors
- Inner and outer drift tubes
- Borders of an electron string
- Bare nuclei (d or $^3$He$^{++}$) target
- Bare nuclei (d or $^3$He$^{++}$) beam (zone of fusion events)

50 mm
Expected counting rates
Conclusion(1)

• The fusion cross section of $^3\text{He} (^3\text{He},2p)^4\text{He}$ at the center of mass energy of 30-50 keV has been measured by using helium-3 doubly ionized beam at a low energy high current accelerator facility OCEAN.

• Free from molecular interference in the beam the measurement determined the astrophysical S-factor with better statistical and systematical errors than previous data.
Conclusion(2)

- By the latest measurements at 30- and 28 keV preliminary results are obtained, and deduced S-factor are

\[
\begin{align*}
S &= 6.89(\pm 0.277) \text{ MeV*barn} \\
S &= 7.99(\pm 0.419) \text{ MeV*barn}
\end{align*}
\]

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Conclusion(3)

• The importance of atomic effect for charged particle nuclear astrophysics experiment has been stressed
• Not only experimental but also theoretical approach for this issue will open a new field for study of laboratory cosmic nuclear and elementary physics
• A few experimental tools for this study have been proposed