Status of the Standard Solar Model and Predictions for Solar Neutrino Fluxes

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1. The Standard Solar Model
   Helioseismology, Chemical Composition

2. The Standard Solar Model
   Nuclear Physics/ Radioactive Beam, GSI, RIKEN

3. Future Prospects for New Physics
   pp Neutrinos

Korean Physical Society/ LENS, October 20, 2005
The Laboratory for Nuclear Science
At Avery Point
$^{56}\text{Ni(}\beta^-)^{56}\text{Co(}\beta^-)^{56}\text{Fe}$

$\tau = 9\text{D} \quad 112\text{D}$
SNO Salt Phase Result:

\[ \Phi_{\nu} = 4.94 \pm 0.21 \text{ (stat)} \pm 0.38^{+0.38}_{-0.34} \text{(syst)} \times 10^6 \text{ cm}^{-2}\text{sec}^{-1} \]  \hspace{1cm} [1]

\[ \frac{\Phi_{SSM}}{\Phi_{\nu}} = 1.17 \]  \hspace{1cm} [2]


SOLAR FUSION

\[ ^1H + ^1H \rightarrow ^2D + e^+ + \nu_e \]
\[ ^2D + ^1H \rightarrow ^3He + \gamma \quad \text{PPI - 86\%} \]
\[ ^3He + ^3He \rightarrow ^4He + 2^1H \]

\[ ^3He + ^4He \rightarrow ^7Be + \gamma \]
\[ ^7Be + e^- \rightarrow ^7Li + \nu_e \quad \text{PPII - 14\%} \]
\[ ^7Li + ^1H \rightarrow 2^4He \]

\[ ^7Be + ^1H \rightarrow ^8B + \gamma \]
\[ ^8B \rightarrow ^8Be + e^+ + \nu_e \quad \text{PPIII - 0.01\%} \]
\[ ^8Be \rightarrow 2^4He \]
Surface Composition of the Sun:

\[ X + Y + Z = 1 \]

\[ P + \text{He} + \text{Heavy} \]
## BS05 Fractional Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$^8$B</th>
<th>$^7$Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-p</td>
<td>0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>$^3$He + $^3$He</td>
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<td>0.02</td>
</tr>
<tr>
<td>$^3$He + $^4$He</td>
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</tr>
<tr>
<td>p + $^7$Be</td>
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<td>0.00</td>
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<tr>
<td>Composition</td>
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<tr>
<td>Opacity</td>
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<td>0.03</td>
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<tr>
<td>Diffusion</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.03</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Weizmann Result, 2004

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \text{gamma} \]
Back Scattering of 2.5 MeV Protons
($^3$He Implanted Target)
\[ \sigma_{17} = \frac{S_{17}}{E} \times e^{-2\pi \eta} \]

(\( \eta = \frac{Z_1Z_2\alpha}{\beta} \)) \quad E_{cm} = 18 \text{ keV}
Seattle Result on $^{7}\text{Be} + p \rightarrow ^{8}\text{B} + \gamma$:

$$S_{17}(0) = 21.4 \pm 0.5 \text{ (expt)} \pm 0.6 \text{ (theory)} \text{ eV-b}$$

[1]

Previous Compilation:

$$S_{17}(0) = 19 \pm 4 -2 \text{ eV-b}$$

[2]


Modern Direct Capture

$^7\text{Be}(p,\gamma)^8\text{B}$

$S_{17}$ (eV·b) vs. $E_{cm}$ (keV)

- Red circles: Weizmann (03)
- Open circles: Seattle (03)
- Open circles: Orasy (01)
- Crosses: Bochum (01)
CAPTURE REACTION: \[ ^7 \text{Be} + p \rightarrow ^8 \text{B} + \eta \]

PRIMA KOFF (1951):

ENHANCEMENT: (I) \( \frac{\pi}{k^2} \lesssim 1,000 \)
(II) \( m_\eta(E_\gamma) \lesssim 1,000 \)

Baur, Bertulans, Rebel - 1986
$|P_{^{7}\text{Be}} + P_p|^2 = M^2$
\( ^7\text{Be}(p,\gamma)^8\text{B} \)

(M1 - 1\(^+\))

(M1 - 3\(^+\))

S17 (eV-b)

\( E_{cm} \) (keV)

RIKEN II (95)
RIKEN I (94)
Filippone et al. (83)
Vaughn et al. (70)
Kavanagh et al. (69)
Parker (66)
When a Dog Speaks it Does Not Matter What it Says.

Igal Talmi
FIG. 4: Artist’s view of the experimental setup. Shown schematically are the beam-tracking detectors (PPAC) in front of and the fragment-tracking Si strip detectors (SSD) behind the Coulomb-breakup target. Proton and $^7\text{Be}$ positions in the focal plane of the KaoS magnetic spectrometer are determined by large-area multi-wire chambers (MWPC) followed by a scintillator-paddle wall for trigger purposes.

FIG. 5: Schematic view of the geometrical arrangement of the four layers of single-sided Si strip detectors yielding the breakup particles’ trajectories directly after the target.

from the measured positions. As a tool for these Monte-Carlo simulations the program package GEANT-3 [35] was used.

The Monte-Carlo simulations started with an event generator that simulated CD of $^8\text{B}$ on $^{208}\text{Pb}$ in first-order perturbation theory or via a fully dynamical calculation by the theoretical approaches mentioned above (subsect.II.B). Technically, the event generator produced statistically-distributed ensembles of 500,000 CD-“events” each that were used as input to a GEANT simulation of the passage of each breakup particle through the Pb target, the SSD detectors, the beamline exit window, the He-filled interior of the magnets and the air behind KaoS before hitting the MWPC volumes. At the target, the emittance of the $^8\text{B}$ as measured with the PPAC’s was imposed, the momentum spread was assumed to be the nominal FRS momentum acceptance, $\Delta p/p = \pm 1\%$.

Moments of each particle type ($p, ^7\text{Be}, ^8\text{B}$) were obtained from two position measurements in the SSD and one position measurement in the respective MWPC. To calculate each particle type’s momentum, a 36-term polynomial expression was derived: its parameters were obtained in a GEANT simulation by sending particles with known momenta (covering evenly the range of relevant momenta) through the setup and fitting the momenta as a function of the positions by varying the 36 polynomial parameters. In a similar way, the invariant-mass resolution of the experiment could be obtained by simulating breakup events of known invariant mass and reconstructing this quantity from the simulated positions. The top panel in Fig.6 shows the $E_{\text{rel}}$ resolution (1$\sigma$ width) as a function of the $p-^7\text{Be}$ relative energy, $E_{\text{rel}}$, as determined from the simulation.

The efficiency of our setup at high $E_{\text{rel}}$ is mainly given by the finite sizes of the SSD and MWPC detectors. Below the maximum around 0.5 to 1 MeV, the efficiency drops due to overlap of the proton- and $^7\text{Be}$ hit patterns in the SSD leading to apparent multiplicity 1 instead of 2. Numerical values of the efficiency could be obtained by simulating the full set of 500,000 CD events with and without the above conditions and plotting the ratios of these numbers for different, evenly spaced $E_{\text{rel}}$ bins. This distribution is shown in the lower panel of Fig.6. The upper set of data points (circles) is obtained by requiring two separated p-Be hits inside all detector volumes. The lower set of data points (squares) is obtained by taking into account the intrinsic detector and trigger efficiencies and applying all analysis conditions, see subsect. IV.B below. It can be seen that the major part of the $E_{\text{rel}}$ distribution is covered with high total efficiency (about 30-40%). It should be noted that this curve is insufficient to correct measured data for efficiency: the total efficiency is a multi-dimensional function of both the original and the smeared-out (by the experimental resolution) angles and momenta of both particles. Therefore, we pass the
FIG. 12: In-plane transverse momenta, \( p_t \), of the breakup protons for three different cuts in \( \theta_8 \). The theoretical curves (full red lines: E1 multipolarity, dashed blue lines: E1+E2 multipolarity) have been calculated in first-order perturbation theory. They were normalized individually to the data sets in each frame.

By comparing Fig.12 with similar plots in our earlier Letter (Fig.2 of Ref.[12]) one can see the improvement in the GEANT simulation which was achieved by the modified prescription for the p-Be hit resolution (see subsect. IV.3.1). The dips near \( p_t \approx 0 \) in the theoretical distributions are now much closer to the experimental ones (though small residual discrepancies are still visible in the rightmost panel).

Fig.13 depicts the experimental \( \theta_{cm} \) distributions for three different \( E_{rel} \) bins, as indicated in the figure. A “safe” \( \theta_8 \) limit of 1° was chosen. As expected, these distributions are mostly isotropic at low \( E_{rel} \) (indicative of s-waves) and become increasingly anisotropic for larger values (contributions from higher orbital angular momenta). As in Fig.12, also for the \( \theta_{cm} \) distributions the calculations for pure E1 multipolarity fit all spectra well; inclusion of an E2 component may lead to a slightly better fit at low \( E_{rel} \), but diverges clearly for the large-\( E_{rel} \) bin where E2 should play a major role. The calculations with a dynamical model will be discussed below.

2. Comparison to dynamical calculations

As mentioned above, Esbensen et al. [30,31] suggested that dynamical calculations are required to properly describe CD and to evaluate \( S_{17} \) from the measured CD cross sections. A sensitive test if such a theory describes the experimental data better than first-order PT calculations is given by comparing the dynamical predictions (using the model described in subsect. II.B.2) to the same angular distributions (bottom part in Fig.13). In all three frames shown, our E1-only dynamical calculations do not agree well with the data points. Dynamical calculations with E1+E2 seem to introduce a slight improvement as long as the effect of E2 multipolarity is small, but a major discrepancy shows up when E2 should have a stronger influence (rightmost lower panel in Fig.13).

We conclude that within the limits of our experimental conditions the simplest model (first-order PT with E1 multipolarity only) still gives the best agreement with the measured center-of-mass proton angular distributions. This is in line with conclusions drawn by Kikuchi et al. [10] and by Iwasa et al. [12] from their respective \( \theta_8 \) distributions (which are, however, less sensitive to a small E2 component than the present angular correlations). Our findings contradict the conclusions of Davids et al. [11] that a substantial E2 cross section has to be subtracted from the total measured CD cross section.

What remains to be done is to find a physical explanation for the small E2 strength compared to the model calculations (both, the potential model and the cluster model, predict almost equal \( S_{17}^{E2} \) values). At the same time, one has to find a different way to explain the asymmetries found in inclusive longitudinal-momentum distri-
Comment on "E2 contribution to the $^8B\rightarrow p + ^7Be$ Coulomb dissociation cross section"

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(Received 25 May 1994)

![Graph showing Coulomb Dissociation of $^8B$ - 600 keV](image)

FIG. 1. The reduced $\chi^2$ obtained from fitting the 600 keV angular distribution of the RIKEN data [3] with $\sigma_{CD}(E1) + \sigma_{CD}(E2)$, as discussed in the text.
Coulomb Dissociation of $^8$B

Extrapolation/ DB(94) [Other Yield Smaller $S_{17}(0)$]
Slope of data $S' = dS/dE$
$S_{17}$ (eV·b)

$d/s(0) = 8.5\%$

$d/s(0) = 6.5\%$

$S + D$

$S$

$D$

$E_{cm}$ (keV)

$S_{17}$ (eV·b)

$7\text{Be}(p,\gamma)^8\text{B}$

$E_{cm}$ (keV)
$^7\text{Be} + p \rightarrow ^8\text{B} + \gamma$
$^7\text{Be}(p,\gamma)^8\text{B}$

- Descouvemont x 0.81
- Typel x 0.77

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![Graph showing $^7\text{Be}(p,\gamma)^8\text{B}$](image)
Seattle Result on $^7Be + p \to ^8B + \gamma$:

\[ S_{17}(0) = 21.4 \pm 0.5 \text{ (expt)} \pm 0.6 \text{ (theory) eV-b} \]  \[ [1] \]

Previous Compilation:

\[ S_{17}(0) = 19 +4 -2 \text{ eV-b} \]  \[ [2] \]

Reasonable Conservative Estimate:

\[ S_{17}(0) = 21.4 \pm 0.8 \text{ (expt)}^{+0.0}_{-3.0} \text{ (extrap)} \text{ eV-b} \]  \[ [3] \]


The Neutrino Matrix:

• We recommend, as a high priority, that a phased program of sensitive searches for neutrinoless nuclear double beta decay be initiated as soon as possible.

• We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos.

• We recommend the development of a spectroscopic solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary pp fusion process in the sun.
Artist’s Rendition of CLEAN
Solar Composition:

$^8\text{B Flux error down from 20\% to 12\%}$
Confrontation with SSM
Must be resolved

$^8\text{B Solar Neutrino Flux:}$
$S_{34}$ soon will be known (<5\%)
$S_{17}$ Seattle result must be checked
Extrapolation must be checked

Is SSM/Flux = 1.17 significant?

$\text{pp Solar Neutrino Flux:}$
Most Exciting Frontier (CLEAN)