NUCLEAR ASPECTS OF THE SOLAR NEUTRINO PROBLEM

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1. Introduction

The solar neutrino problem has its origin in the discrepancy between the observed terrestrial neutrino fluxes of the neutrinos produced by nuclear reactions in the solar core and the predicted neutrino fluxes by standard solar models (SSM’s) (Bahcall, 1989; Bahcall and Pinsonneault, 1995; Castellani et al., 1997). The observation of the solar neutrinos is of decisive importance, because it allows us contrary to the observed solar electromagnetic radiation to look into the nuclear active zone in the core of the sun, since the solar mantle is practically transparent to neutrinos.

The observed neutrino fluxes are substantially less than predicted by SSM’s. Roughly speaking the Homestake chlorine-detector (Davis et al., 1968; Cleveland et al., 1995), the neutrino-electron scattering detector KAMIOKANDE (Hirata et al., 1989; KAMIOKANDE Collaboration, 1995), and the gallium detectors GALLEX (GALLEX Collaboration, 1994; GALLEX Collaboration, 1996) and SAGE (Abazov et al., 1991; SAGE Collaboration, 1996) observe approximately the fractions 3/10, 4/10, and 5/10 of the predicted solar neutrino flux, respectively (see Table I). Recently, the reliability of the measuring method of the GALLEX collaboration was tested with an artificial neutrino source, resembling the solar neutrino spectrum that was inserted in the gallium tank (Hampel et al., 1996). The measured neutrino flux was $(92 \pm 8)\%$ of the expected value. This result improves significantly the credibility of the obtained values for the measured solar neutrino flux in the GALLEX detector.

The present values and their $1\sigma$ errors of the different neutrino detectors are shown in Table I. There are three different nuclear reactions in the pp-chains of the sun emitting the bulk of solar neutrinos (Fig. 1):

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Table I. The present different neutrino detectors with their detection reactions, threshold energies and the detected neutrino flux. In the last column the the result obtained using a standard solar model (SSM) are given.

| Neutrino detector detection reaction | threshold energy$^{a}$ | Observed result$^{b}$ | SSM$^{c}$ result$^{b}$ |
|--------------------------------------|------------------------|-----------------------|------------------------|
| Homesteak $\nu + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$ | 0.814 MeV | $2.55 \pm 0.17 \pm 0.18^{d}$ | $9.3^{+1.2}_{-1.4}$ |
| KAMIOKANDE $\nu + e^- \rightarrow \nu + e^-$ | 7 MeV | $2.73 \pm 0.17 \pm 0.34^{e}$ | $6.62 \times (1.00^{+0.14}_{-0.17})$ |
| GALLEX $\nu + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}$ | 0.233 MeV | $69.7^{+7.8f}_{-8.1}$ | $137^{+5}_{-7}$ |
| SAGE $\nu + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}$ | 0.233 MeV | $69 \pm 10^{+5g}_{-7}$ | $137^{+8}_{-7}$ |

$^{a}$ Energy in MeV
$^{b}$ in $10^{6} \text{cm}^{-2} \text{s}^{-1}$ for KAMIOKANDE; in SNU ($10^{-36}$ captures per target atom and seconds) for the others
$^{c}$ Bahcall and Pinsonneault, 1995
$^{d}$ Cleveland et al., 1995
$^{e}$ KAMIOKANDE Collaboration, 1995
$^{f}$ GALLEX Collaboration, 1996
$^{g}$ SAGE Collaboration, 1996

(i) Two-proton fusion: $p + p \rightarrow D + e^+ + \nu_e$ (pp-neutrinos)
(ii) Electron capture by $^7\text{Be}$: $^7\text{Be}(e^-,\nu_e)^7\text{Li}$ (Be-neutrinos)
(iii) Beta-decay by $^8\text{B}$: $^8\text{B}(,e^+\nu_e)^8\text{Be}$ (B-neutrinos).

The flux of other solar neutrino sources (pep- and CNO-neutrinos) is much weaker.

The spectrum of the solar neutrinos as predicted by SSM’s is depicted in Fig. 2. In this figure also the thresholds of the different neutrino detectors are indicated. The pp-neutrinos can only be detected by the gallium detectors, whereas the neutrino-electron scattering detector can only detect the B-neutrinos.

In this article we investigate in Sect. 2 the nuclear reactions determining mainly the solar neutrino flux. In Sect. 3 we discuss the new reaction rate for the reaction $p + p \rightarrow D + e^+ + \nu_e$ using a relativistic field theory model of the deuteron. Some consequences of this new reaction rate for the solar neutrino flux are presented and discussed in Sect. 4.
2. Nuclear reactions determining the solar neutrino flux

The nuclear reactions relevant for the solar neutrino flux are:
(i) The basic nuclear reaction in the solar core: \( p + p \rightarrow D + e^+ + \nu_e \)
(ii) The reactions determining the branching ratio between the ppI- and (ppII+ppIII)-chains (see Fig. 1): \(^3\text{He}(^3\text{He},2p)^4\text{He}\) and \(^3\text{He}(^4\text{He},\gamma)^7\text{Be}\)
(iii) The reactions determining the branching ratio between the ppII- and ppIII-chains (see Fig. 1): \(^7\text{Be}(e^-\nu_e)^7\text{Li}\), and \(^7\text{Be}(p,\gamma)^8\text{B}\).

The low-energy electroweak model and non-relativistic approaches, having been applied to the computation of the contribution of strong interactions to the matrix element of the \( p + p \rightarrow D + W^+ \) transition (Bethe and Critchfield, 1939; Bahcall and Pinsonneault, 1992; Kamionkowski and Bahcall, 1994) do not leave room for a substantial change of the cross section magnitude. As has been noted by Castellani et al., 1997 they differ from the mean value by no more than 3%.

The values of the astrophysical S-factors for the reactions \(^3\text{He}(^3\text{He},2p)^4\text{He}\) and \(^3\text{He}(^4\text{He},\gamma)^7\text{Be}\) are estimated to be known within about ±4% (Castellani et al., 1997). Recently, it was possible to measure the reaction \(^3\text{He}(^3\text{He},2p)^4\text{He}\) down to the energies of the solar Gamow peak (Arpesella et al., 1996). This reduced the uncertainty of the astrophysical S-factor for this reaction by about another factor of 2. Furthermore, no sign of a hypothetical resonance at the energies of the solar Gamow peak was found for this reaction.

The \(^7\text{Be}\) electron capture rate \(^7\text{Be}(e^-\nu_e)^7\text{Li}\) has recently been investigated by Gruzinov and Bahcall, 1997. The total theoretical uncertainty in the electron capture rate under solar conditions has been found to be about 2%. The largest uncertainty is the value of the astrophysical S-factor of \(^7\text{Be}(p,\gamma)^8\text{B}\). It is estimated to be known only within approximately ±10% (Castellani et al., 1997). However, because the ppIII-chain is so weak compared to the ppII-chain (see Fig. 1), only the \(^8\text{B}\) solar neutrino flux is significantly changed by this uncertainty.

Summarizing, by using the above discussed uncertainties in the astrophysical S-factors and reaction rates there seems to be no possibility to relax the solar neutrino problem in the framework of pure nuclear physics. This has already been noticed before by many authors.

3. A new reaction rate for \( p + p \rightarrow D + e^+ + \nu_e \)

A substantial enhancement of the reaction rate for the two-proton fusion \( p + p \rightarrow D + e^+ + \nu_e \) by a factor of about 2.9 with respect to the potential approach has been found recently (Ivanov et al., 1997)
within a relativistic field theory model of the deuteron (Ivanov et al., 1995). This model has been constructed in analogy with the $\sigma$-model and the extended Nambu-Jona-Lasinio model (Itzykson and Zuber, 1980; Alfaro et al., 1973; Nambu and Jona-Lasinio, 1961).

This result is due to our model approach using one-nucleon loop diagrams for the description of strong low-energy interactions of the deuteron to other particles. It is well-known that such fermion loop diagrams should possess anomalies (Adler, 1969; Bell and Jackiw, 1969; Bardeen, 1969; Gertsein and R. Jackiw, 1969; Brown et al., 1969). As usually, these anomalies dominate the amplitudes of strong low-energy interactions of hadrons (Adler, 1969; Wess and Zumino, 1961; Ivanov and Shechter, 1980; Ivanov, 1981). In the case of the two-proton fusion we encounter the dominance of the anomaly of the AAV one-nucleon loop diagrams, that is the diagrams having two axial-vector and one vector vertices. This is the reason why our result cannot be reduced to the obtained value in the potential approach.

In the low-energy limit when the 3-momenta of interacting protons tends to zero the amplitude of the process $p + p \rightarrow D + e^+ + \nu_e$ reads (Ivanov et al., 1997)

$$
\mathcal{M}(p + p \rightarrow D + e^+ + \nu_e) =

i C(v) g_A M_N G_F \frac{3g_V}{4\pi} \epsilon^*_\mu(Q) [\bar{u}(k_\nu) \gamma^\mu(1 - \gamma^5)v(k_e)] \times

\frac{g_{\pi NN}^2}{8M^2_\pi} \left(1 - \frac{8\sqrt{2\pi} M^2_\pi}{g_{\pi NN}^2 M_N} a_S\right) \left[\bar{u}(p_1) \gamma^5 u(p_2)\right], \quad (1)
$$

where $a_S$ is the $^1S_0$ pp scattering length the experimental value of which is $a_S = (-17.1 \pm 0.2) \text{ fm}$ (Ivanov et al., 1997).

The cross section of the reaction $p + p \rightarrow D + e^+ + \nu_e$ is given by

$$
\sigma(p + p \rightarrow D + e^+ + \nu_e) =

\frac{C^2(v)}{v} \frac{9g_A^2 G_F^2 Q_D}{1280\pi^5} \varepsilon_D^5 M^3_N f \left(\frac{m_e}{\varepsilon_D}\right) \times

\frac{\left(\frac{g_{\pi NN}^2}{8M^2_\pi}\right)^2 \left(1 - \frac{8\sqrt{2\pi} M^2_\pi}{g_{\pi NN}^2 M_N} a_S\right)^2}{1 + \left[\frac{g_{\pi NN}^2}{8M^2_\pi}\right]^2 \left(1 - \frac{8\sqrt{2\pi} M^2_\pi}{g_{\pi NN}^2 M_N} a_S\right)^2 \left(\frac{M_N}{4\pi^2 v^2}\right)^4} =
$$
The cross section is calculated in units of $\hbar = c = 1$. All parameters in the above equations are defined in Ivanov et al., 1997. The appearance of the factor $C(v) = \sqrt{2\pi\alpha/v} \exp(-\pi\alpha/v)$ taking into account the Coulomb repulsion between protons at low energies agrees with the result obtained by Bethe and Critchfield, 1939. The reaction rate is then given by (Ivanov et al., 1997)

$$< v \sigma (p + p \rightarrow D + e^+ + \nu_e) > = 1.03 \times 10^{-39} \times \frac{1}{\alpha} \times \frac{2}{\pi} \times \left(\frac{1}{3}\right)^2 \times \frac{\tau^2 e^{-\tau}}{3(1 + 52743 \frac{3\alpha^2\pi^2}{\tau})} = 1.03 \times 10^{-38} \frac{\tau^2 e^{-\tau}}{1 + \frac{83}{\tau}} \text{cm}^3 \text{s}^{-1},$$

where $\tau$ is connected with the temperature (Bethe and Critchfield, 1939)

$$\tau = 3 \left(\frac{\alpha^2\pi^2 M_N}{4kT}\right)^{1/3}.$$  

The temperature dependence of Eq. (3) coincides fully with that derived by Bethe and Critchfield, 1939. Setting $T = T_c = 15.5 \times 10^6$ K, where $T_c$ is the temperature of the solar core in the Standard Solar model (Rolfs and Rodney, 1988), we get $\tau = 13.56$, and obtain the following estimate

$$< v \sigma (p + p \rightarrow D + e^+ + \nu_e) > = 3.44 \times 10^{-43} \text{cm}^3 \text{s}^{-1}.$$  

This value is by a factor of 2.9 larger than the one calculated within the potential approach (Rolfs and Rodney, 1988, see also Bahcall, 1989 and Kamionkowski and Bahcall, 1994). The magnitude of the theoretical uncertainty of the relativistic field theory model of the deuteron is expected of order $\Delta = \pm 30\%$ (Ivanov et al., 1997).

The enhancement of the amplitude of the $p + p \rightarrow D + W$ transition found in our approach is related to the computation of the amplitude in terms of one-nucleon loop diagrams. Indeed, the structure function in the momentum representation (Ivanov et al., 1997) defining the effective Lagrangian of the $p + p \rightarrow D + W$ transition is due to the contribution of the anomalous part of the AAV one-nucleon loop diagram (Wess and Zumino, 1961; Ivanov and Shechter, 1980; Ivanov,
Table II. Contributions from the main components of the neutrino fluxes (in SNU) for the gallium and chlorine $S_{Ga}$ and $S_{Cl}$ detectors, respectively, according to a SSM and our alternative solar model (ASM). In the last line the summed up neutrino fluxes are compared with the corresponding experimental data. In the last column the parameters $\alpha_i$ of the power-law behavior are shown. The errors are due to the assumed 30% uncertainty of the reaction rate for $p + p \rightarrow D + e^+ + \nu_e$.

|     | $S_{Ga}$ |     | $S_{Cl}$ |     | $\alpha_i$ |
|-----|----------|-----|----------|-----|------------|
|     | SSM$^a$  | our model | experiment$^b$ | SSM$^b$ | ASM | experiment$^c$ |
| pp  | 69.7     | 75.1$^{+1.1}_{-1.9}$ | 0.00 | 0.00 | 0.07 |
| pep | 3.0      | 3.2$^{+0.0}_{-0.0}$ | 0.22 | 0.24$^{+0.0.01}_{-0.0.01}$ | 0.07 |
| $^7$Be | 37.7      | 37.7$^{+2.9}_{-2.9}$ | 1.24 | 0.39$^{+0.17}_{-0.10}$ | 1.1 |
| $^{13}$N | 3.8       | 0.4$^{+0.2}_{-0.4}$ | 0.11 | 0.04$^{+0.01}_{-0.01}$ | 2.2 |
| $^{15}$O | 6.3       | 0.6$^{+0.3}_{-0.6}$ | 0.37 | 0.04$^{+0.04}_{-0.01}$ | 2.2 |
| $^8$B | 16.1      | 0.9$^{+0.4}_{-1.5}$ | 7.36 | 0.42$^{+0.22}_{-0.07}$ | 2.7 |
| Sum | 136.6     | 91.9$^{+2.9}_{-6.2}$ | 77.1$^{+13.4}_{-13.4}$ | 9.30 | 1.10$^{+0.33}_{-0.88}$ | 2.55$^{+0.13}_{-0.35}$ |

$^a$ Bahcall and Pinsonneault, 1995
$^b$ GALLEX Collaboration, 1996
$^c$ Cleveland et al., 1995
$^d$ Castellani et al., 1997

1981). Such an anomalous contribution, produced by vacuum fluctuations of virtual nucleons, has a quantum-field-theory nature and cannot be obtained within the potential approach describing strong low-energy interactions of the protons and the deuteron in terms of the overlap integral of the wave functions of two protons and the deuteron. The ambiguity of the computation of the AAV-anomaly, produced by the shift of the virtual nucleon momentum, has been fixed by the requirement of gauge invariance under gauge transformations of the deuteron field (Ivanov et al., 1997). This is very similar to the removal of the ambiguity appearing for the computation of the Adler-Bell-Jackiw-Bardeen anomaly (Adler, 1969; Bell and Jackiw, 1969; Bardeen, 1969).

4. Discussion

One of the possible relaxations of the solar neutrino problem is to lower the temperature in the center of the sun in comparison to that predicted by SSM’s as $T_c = 15.5 \times 10^6$ K (Rolfs and Rodney, 1988).
Table III. Contributions from the main components of the neutrino fluxes (in $10^6 \text{cm}^{-2}\text{s}^{-1}$) for the KAMIOKANDE detector according to a SSM and our alternative solar model (ASM). In the last line the neutrino flux is compared with the corresponding experimental data. In the last column the parameter $\alpha_i$ of the power-law behavior is shown. The errors are due to the assumed 30% uncertainty of the reaction rate for $p + p \to D + e^+ + \nu_e$.

| $^8\text{B}$ | $^7\text{Be}$ | $^{13}\text{N}$ | $^{15}\text{O}$ | $^8\text{B}$ |
|-------------|-------------|-------------|-------------|-------------|
| $S_{\text{Kam}}$ | $S_{\text{SSM}}$ | $S_{\text{ASM}}$ | $S_{\text{experiment}}$ | $\alpha_i$ |
| $6.62$ | $0.37^{+0.19}_{-0.19}$ | $0.37^{+0.19}_{-0.19}$ | $2.73\pm0.51$ | $-2.7$ |

$^a$ Bahcall and Pinsonneault, 1995  
$^b$ KAMIOKANDE Collaboration, 1995  
$^c$ Castellani et al., 1997

Indeed, due to strong dependence of the solar neutrino fluxes on $T_c$ just a 20 to 30% diminishing of $T_c$ leads to a suppression of the neutrino fluxes by more than an order of magnitude (Castellani et al., 1997). In order to reduce $T_c$ one can resort to the change of physical and chemical phenomenological inputs which determine the structure of the star (Castellani et al., 1997). A process which influences substantially the temperature in the center of the sun is the reaction $p + p \to D + e^+ + \nu_e$. The magnitude of the reaction rate for $p + p \to D + e^+ + \nu_e$ is directly related to the solar luminosity that must be reproduced by any solar model. Therefore, an enhancement of the cross section magnitude of two-proton fusion leads to a decrease of $T_c$ that suppresses the solar neutrino fluxes for the high-energy solar neutrinos (Castellani et al., 1997). In order to reconcile the enhancement of our new reaction rate for $p + p \to D + e^+ + \nu_e$ by the factor of 2.9 with the solar luminosity we must assume that the temperature in the solar core equals $T_c = 13.8^{+0.4}_{-0.4} \times 10^6 \text{K}$ (Castellani et al., 1997).

The solar neutrino fluxes $\Phi_i$, where $i = pp$, pep, $^7\text{Be}$, $^{13}\text{N}$, $^{15}\text{O}$ and $^8\text{B}$, can be represented in the form of a power-law behavior (Castellani et al., 1997), i.e.,

$$\Phi_i = x^{\alpha_i} \Phi_i^*.$$ (6)
\( \Phi^*_i \) is the neutrino flux, predicted by SSM’s, and the parameter \( x \) in our definition reads
\[
x = \frac{\langle v \sigma(p + p \rightarrow D + e^+ + \nu_e) \rangle}{\langle v \sigma(p + p \rightarrow D + e^+ + \nu_e) \rangle^*} = 2.90 \pm 0.87, \tag{7}
\]
where \( \langle v \sigma(p + p \rightarrow D + e^+ + \nu_e) \rangle^* \) is the quantity calculated in the potential approach.

The values of the parameters \( \alpha_i \) are given in Tables II and III and can be found in Table X of Castellani et al., 1997. In these tables we also show the neutrino fluxes that should give the contributions to the signals detected in the gallium and chlorine and KAMIOKANDE neutrino detectors. We have normalized our predictions to the results obtained with a reference SSM (Bahcall and Pinsonneault, 1995).

It is seen that our alternative solar model (ASM) explains reasonably well the experimental data of the gallium experiments (see Table II, last line). For the neutrino flux measured in the chlorine experiment our model prediction is too small by about a factor of 2 (see Table II, last line). One can see that our prediction for the solar neutrino flux is much too small when compared with the KAMIOKANDE experimental data (see Table III, last line).

Another possibility to compare the results of the neutrino detectors with solar models is in terms of the neutrino fluxes for the Be- and B neutrinos. Roughly speaking the experimental results of the three neutrino detectors imply for the different neutrino fluxes when compared to a SSM (see Tables II and III):

\[
\Phi_{pp} \approx \Phi_{pp}^{SSM}, \tag{8}
\]
\[
\Phi_{Be+CNO} \ll \Phi_{Be+CNO}^{SSM}, \tag{9}
\]
\[
\Phi_B \approx 0.35 \Phi_B^{SSM}. \tag{10}
\]

Therefore, the solar neutrino problem can also be formulated when compared to SSM’s as the problem of the missing Be-neutrinos and the reduced flux of the B-neutrinos.

Using our new reaction rate for \( p + p \rightarrow D + e^+ + \nu_e \) we obtain the following approximate relationship between the experimental results of the three neutrino detectors and our ASM:

\[
\Phi_{pp} \approx \Phi_{pp}^{ASM}, \tag{11}
\]
\[
\Phi_{Be+CNO} \approx \Phi_{Be+CNO}^{ASM}, \tag{12}
\]
\[
\Phi_B \approx 7 \Phi_B^{ASM}. \tag{13}
\]
Table IV. Differences of the neutrino fluxes predicted by SSM’s and our ASM from the values observed by the different neutrino detectors in standard experimental deviations $\sigma$ of the corresponding experiments.

| Neutrino detector  | Deviation of SSM in $\sigma$ | Deviation of ASM in $\sigma$ |
|--------------------|-----------------------------|-----------------------------|
| Gallium detector   | +8                          | +3                          |
| Chlorine detector  | +19                         | −4                          |
| KAMIOKANDE         | +8                          | −5                          |

Therefore, the solar neutrino problem can also be formulated when compared to the ASM as the problem of the excessive B-neutrinos.

A more quantitative calculation gives the following constraints between the detected solar neutrino signals and the B- and (Be+CNO)-fluxes (see Eq. (61) of Castellani et al., 1997):

\[
S_{Ga} = 80.1 + 6.14\Phi_{Be+CNO} + 2.43\Phi_B  
\]

\[
S_{Cl} = 0.248 + 0.236\Phi_{Be+CNO} + 1.11\Phi_B  
\]

\[
S_{Ka} = \Phi_B  
\]

Here $S_{Ga}$ and $S_{Cl}$ are given in SNU, $\Phi_{Be+CNO}$ in $10^9$ cm$^{-2}$ s$^{-1}$, and $S_{Ka}$ and $\Phi_B$ in $10^6$ cm$^{-2}$ s$^{-1}$. The flux of the pp-neutrinos has been eliminated in the above equations by using the solar luminosity constraint, i.e., by assuming that the flux of the pp-neutrinos is constrained approximately by the solar luminosity. The result for each experiment can then be plotted in the $(\Phi_B, \Phi_{Be+CNO})$-plane as shown in Fig. 3. Also in this figure the values of these neutrino fluxes obtained in a standard solar model (SSM) (Bahcall and Pinsonneault, 1995) as well as in our alternative solar model (ASM) with the new reaction rate are shown.

In Table IV the differences of the neutrino fluxes predicted by the SSM and the ASM from the values observed by different neutrino detectors derived from Tables II and III are shown using the standard deviations $\sigma$ of the corresponding experiments. These differences are considerable less in the ASM than in the SSM. A compelling argument for a resolution in terms of new particle physics should rest on a dramatic discrepancy (often estimated at $5\sigma$) between the neutrino detectors and the flux predictions of solar models (Cumming and Haxton, 1996). As can be seen from Table IV such a discrepancy is barely reached when assuming our ASM.
Helioseismological observations are an important tool to investigate the solar interior dynamics and structure with great precision (Christensen-Daalgaard, 1996). Interestingly enough, the sound speed derived from SSM's including element diffusion agrees with helioseismological measurements with a precision better than 0.2% (Bahcall et al., 1997). Even tiny fractional changes in the temperature and the molecular weight would produce measurable discrepancies in the precisely determined helioseismological sound speed. Since the temperature in the solar center for our ASM is about 9% lower than in the SSM, it remains questionable if the sound speed can also be reproduced by the ASM. Investigations in this direction are in progress.

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Figure captions

Fig. 1: The three solar pp-chains
Fig. 2: Spectrum of the solar neutrinos. At the top of the figure the thresholds of the different neutrino detectors are indicated: Ga ... gallium detectors, Cl ... chlorine detector, K II ... KAMIOKANDE detector.
Fig. 3: The $^8$B and $^7$Be neutrino fluxes, consistent with the luminosity constraint and experimental results. The shaded areas correspond to the (best-fit ± 1 $\sigma$) experimental values for the chlorine, gallium and KAMIOKANDE neutrino detectors. The full circles indicate the predictions by a standard solar model (SSM) and our alternative solar model (ASM).
Chain 1

\[ p(p, e^+ \nu)d \]

\[ d(p, \gamma)^3\text{He} \]

\[ ^3\text{He} (\alpha, \gamma)^7\text{Be} \]

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

\[ ^7\text{Be}(e^-, \nu)^7\text{Li} \]

\[ ^8\text{B}(e^+ \nu)^8\text{Be}^* \]

\[ ^3\text{He}(^3\text{He}, 2p)^4\text{He} \]

\[ ^7\text{Li}(p, \alpha)^4\text{He} \]

\[ ^8\text{Be}^*(\alpha)^4\text{He} \]

Chain 2

Chain 3

86% 14%

14% 0.02%
\[ \Phi_B [10^6 \text{cm}^{-2}\text{s}^{-1}] \]

\[ \Phi_{\text{Be+CNO}} [10^9 \text{cm}^{-2}\text{s}^{-1}] \]

- Cl
- ASM
- Ga
- Ka

SSM

Graph showing the comparison between different measurements or predictions of \( \Phi_B \) and \( \Phi_{\text{Be+CNO}} \).