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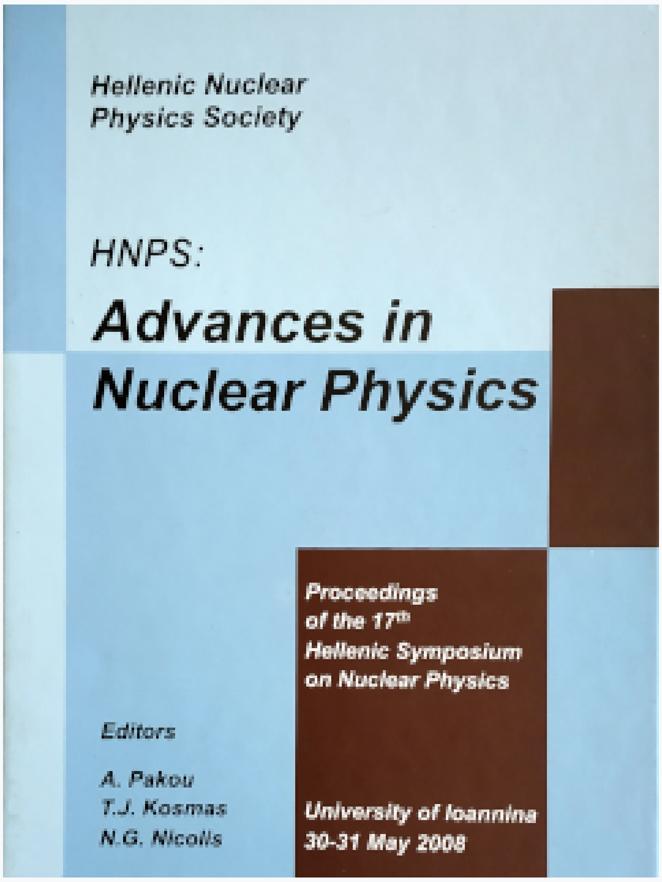

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Revisited solar neutrino fluxes and CNO-cycle lifetimes using recent cross-section factor data from pp-chain reactions

G. I. Karathanou [a], V.Tsikoudi [a], Th. Liolios [b] and T.S. Kosmas [a]

[a] *Theoretical Physics Section, University of Ioannina, GR 45110 Ioannina, Greece*

[b] *Hellenic Army Academy, Department of Physical Sciences & Applications, Vari16673, Attica, Greece*

Abstract

We provide revisited lifetimes for CNO-cycle isotopes using improved radiative opacities and elemental abundances in the context of several solar models. We also employ recent experiments (LUNA) and calculations for the nuclear cross-section factors in order to update solar neutrino fluxes (Φ) for proton-proton chain reactions. We compare them with those obtained by previous theoretical solar models. Currently, we study neutrino-nucleus reactions, the nuclear detector response to neutrinos produced through hep and ^8B thermonuclear reaction channels.

1 Introduction

Hydrogen burning is the first stage of major nuclear burning in the centers of the stars and specifically in the Sun. During this process four protons are being fused to produce ^4H_e as well as e^+, ν_e and γ-radiation and the total energy released is $Q = 26.73MeV$. For hydrogen, there are two main reaction chains, the proton-proton chain and the CNO cycle, the former dominates in lower-main sequence stars ($M < 1,5M_{\odot}$) such as our Sun. In CNO cycle the carbon, nitrogen, and oxygen elements are not consumed, instead they are recycled and act as catalysts.

The key to understanding the CNO-cycle reactions lies in appreciating the lifetimes of the nuclei against protons. In this work we derive effective cross-section factors for the interaction of the ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O and ^{17}O with protons and using data from three different refined solar models we compute lifetimes for these CNO isotopes.

In the last few years there has been a significant progress in the experimental study of low energy nuclear reactions. Existing LUNA and latter Borexino solar neutrino experiments, are expected to determine whether the energy spectrum of electron type neutrinos created in the center of the sun is modified by physics beyond standard electroweak theory. Moreover, will provide precision tests of solar model predictions for the rates at which nuclear reactions occur in the sun.

The LUNA experiment [1] has recently taken measurements down to solar energies, and determine the nuclear cross-section factor with 6% accuracy, which translates into 3% uncertainty in the prediction of the solar neutrino flux. In this work we used these factors in order to update solar neutrino fluxes for proton-proton chain reactions[2].

Several other neutrino-detection terrestrial experiments have been developed in order to study neutrino-nucleus interactions. These reactions enable us to study the neutrino intrinsic properties, the structure of the fundamental electroweak interactions and many astrophysical phenomena that take place in the interior of stars. The most important problem in extracting information from neutrino-nucleus scattering experiments remain the very small interacting cross sections. In this issue we currently devote a special effort on calculating convoluted total cross sections for the coherent and incoherent channels, using the energy spectrum distribution of the hep neutrino sources.

2 The CNO-cycle lifetimes in the context of recent refined solar models

Recent investigations on the cross-section factors for the reactions of ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O and ^{17}O with protons provide the possibility of determining variations of these factors with temperature and their effects on the mean lifetimes, τ, of the nuclei involved.

The cross-section factor $S(E)$ is defined for a thermonuclear reaction by the equation

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

where σ is the reaction cross-section, E is the center-of-mass interaction energy and η is the Sommerfeld parameter.

In stellar problems, the cross-section times relative velocity must be integrated over the Maxwell-Boltzmann distribution in energy, at the temperature, T, of the medium. Expanding $S(E)$ in a Taylor series, the average value for the cross-section times relative velocity becomes

$$\langle \sigma v \rangle = (\frac{2}{\mu k T})^{1/2} (\Delta E_0/kT) S_{eff} \exp(-3E_0/kT) \tag{2}$$

where the quantity S_{eff} is given below as

$$S_{eff} = S(0)[1+\frac{5kT}{36E_0}] + S'(0)E_0[1+\frac{35kT}{36E_0}] + \frac{1}{2}S''(0)E_0^2[1+\frac{89kT}{36E_0}] \tag{3}$$

The S-factor is convenient for extrapolating measured cross sections down to lower astrophysical energies. When $S(E)$ is assumed to be a constant, the integrand is peaked at the "most effective energy" E_0 [3].

The lifetime in years for resonant reactions is given by

$$\frac{1}{\tau_p(X)} = 2.45 \times 10^{16} \frac{\rho X_1}{A_1} f S_{eff} [\frac{Z_1 Z_2}{A T_6^2}]^{1/3} \exp(-B T_6^{-1/3}) yr^{-1} \tag{4}$$

where f is the electron-screening factor and $B = 42.48(Z_1^2 Z_2^2 A)^{1/3}$. For interactions with hydrogen, $X_1 = X_H$, $Z_1 = 1$, $A_1 \approx 1$, $A = A_1 A_2 / A_1 + A_2$ their reduced nuclear mass and $kT = 0.086 T_6$ [4].

Recently, three refined solar models have been developed. In this work we exploit the predictions of them in order to obtain the CNO-cycle lifetimes by using the cross section factors [5].

The first model from J. N. Bahcall, M. H. Pinsonneault and S. Basu [6] uses older radiative opacities and heavy element abundances from Grevesse and Sauval (1998). Predicted neutrino fluxes differ by several standard deviations from observed experimental solar neutrino fluxes (GALLEX, Kamiokande, etc.). This model is in (relatively) good agreement with the results from helioseismology (sound speed, depth of the convection zone etc.). The second model BS05(AGS, OP) [7] uses new lower heavy element abundances taking from Asplund et al. (2005) and OP opacities. The predictions of this model are in disagreement with helioseismological measurements. The third model BS05 (OP) [7] uses older higher heavy element abundances and new OP opacities. The predictions of this model give much better agreement with helioseismological measurements.

In Table 1 we show some representative calculated results for the lifetimes in CNO-cycle based on the predictions of the above models. This table contains the $\log(\tau \rho X_H/100)$ which is presented over the temperature range 3×10^6 to 15×10^6 degrees for the $C^{12}(p+\gamma)N^{13}$ proton reaction in the CNO-cycle, where

Table 1
Dependence of $\log(\tau\rho X_H/100)$ on temperature for the ^{12}C nuclei which take place in the $C^{12}(p+\gamma)N^{13}$ reaction in the context of three different refined solar models.

T_6	BPB [6]	BS(AGS, OP)[7]	BS(OP)[7]
3.996	20.92073	20.86104	20.95292
6.999	13.72399	13.61986	13.6851
9.953	9.92206	9.88269	9.9194
13.000	7.42201	7.39552	7.41307
15.000	6.23481	6.21463	6.22915

ρ is the density and X_H the hydrogen concentration by mass (the factor 100 is introduced as an order-of-magnitude value for ρX_H in main-sequence stars such as the Sun) [4]. As can be seen from Table 1 the results for the lifetimes are not significantly affected by the choice of heavy-element abundances or the radiative opacities.

3 Solar neutrino fluxes using resent LUNA cross-section factors

The various standard solar models contain several low-energy nuclear cross-section factors and other parameters. Here we examine the dependence of the solar neutrino fluxes on these factors. The most important fluxes for solar neutrino experiments are the low energy pp neutrinos $\Phi(pp)$, the intermediate energy ^7Be line neutrinos $\Phi(^7Be)$, and the rare high energy ^8B neutrinos $\Phi(^8B)$.

The relative rates of the $^3He(\alpha,\gamma)^7Be$ and $^3He(^3He,2p)^4He$ reactions determine what fractions of pp-chain results in ^7Be or ^8B neutrinos. So, if S_{33} and S_{34} be the low energy nuclear cross-section factors for these reactions then

$$\Phi(pp) \propto S_{33}^{0.03} S_{34}^{-0.06}\,, \quad \Phi(^7Be) \propto S_{33}^{-0.43} S_{34}^{0.86}\,, \quad \Phi(^8B) \propto S_{33}^{-0.40} S_{34}^{0.81} \quad (5)$$

Recently LUNA collaboration [1] have derived zero-energy astrophysical factors $S_{33}(0) = (5.32 \pm 0.08)$ MeV b and $S_{34}(0) = (0.560 \pm 0.017)$ keV b for the reactions $^3He(^3He,2p)^4He$ and $3He(\alpha,\gamma)^7Be$. These values give updated solar neutrino fluxes [8]. Terrestrial experiments require exact description of these fluxes for all possible neutrino sources.

In the rest of the paper we deal with the response of various nuclear detectors to such neutrino sources.

4 Solar neutrino detection by nuclear targets

In neutral-current neutrino-nucleus processes, considered in the present work, intermediate energy solar neutrinos are elastic scattered from a nucleus (A,Z) via the exchange of neutral Z_0 bosons. Such reactions are represented by

$$\nu + (A, Z) \rightarrow \nu' + (A, Z)^* \tag{6}$$

At low energies, relevant for solar neutrinos, the nuclear detector can be treated as a point scatterer mostly remaining in its ground state. In such cases nucleons respond coherently. Therefore the general expression for the differential cross section in a good approximation reduces to

$$\frac{d\sigma}{d(cos\Phi)} = G^2 \frac{sin^2\theta_w}{2\pi} A^2 E_\nu^2 (1 + cos\Phi) \tag{7}$$

where $A = N + Z$, (N and Z are the neutron and proton numbers), Φ the scattering angle, θ_w the Weinberg angle and E_ν the energy in MeV [9]. Integrating over all directions, the total cross section for nuclei with even-even $(J = 0)$ and N=Z is $\sigma \approx 4 \times 10^{-43} N^2 E_\nu^2 cm^2 MeV^{-2}$.

The coherence factor A^2 in Eq. (7) and the factor N^2 in equation below represent one of the main advantages of using neutrino-nucleus elastic scattering. For practical cases, the cross section can be a factor of $10^3 - 10^4$ larger than the corresponding neutrino absorption and neutrino-electron scattering process.

We must notice that the main difficulty in studying neutrino-nucleus scattering is that the only observable effect is the nuclear recoil. The average energy of this effect is

$$\langle E_\nu \rangle = \frac{2}{3A} (\frac{E_\nu}{1MeV})^2 keV \tag{8}$$

Hence, the nuclear-target must be chosen carefully because the cross section increases as N^2 and the recoil energy decreases inversely as the mass number A.

In principle, coherent scattering could be used to detect all of the solar neutrino sources. In practice, the ^8B and hep neutrinos (intermediate energy solar

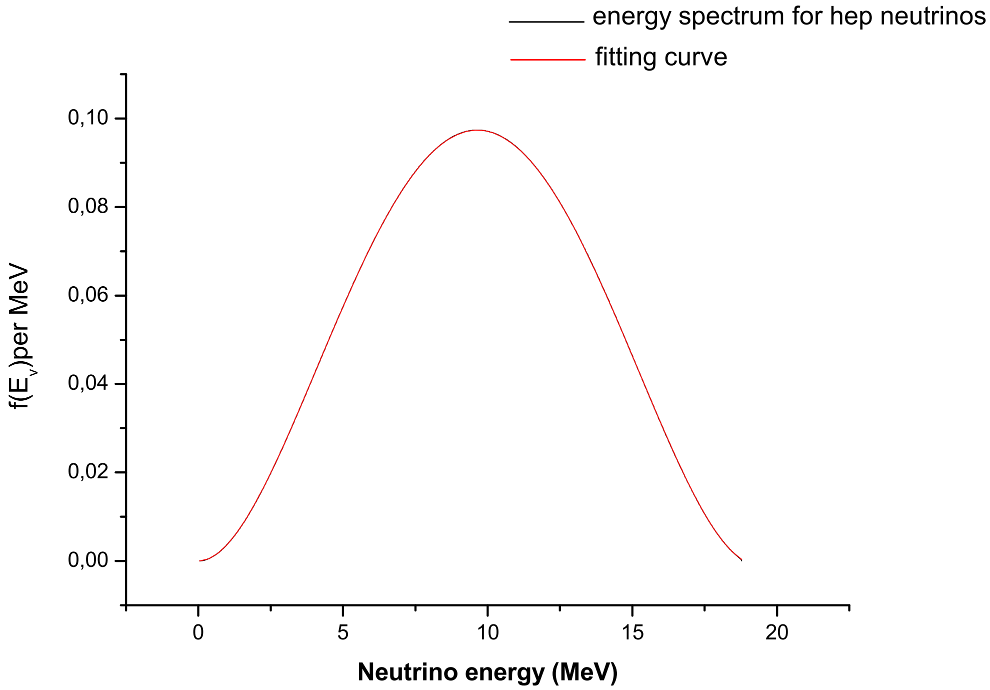

Fig. 1. The hep neutrino energy spectrum obtained in the context of the standard solar model.

neutrinos) which may have higher energies, may be easier to detect since both the coherent scattering cross section and the magnitude of the nuclear recoil are proportional to the square of the neutrino energy [10].

In this work we focus on the study of the response of concrete nuclei in the hep energy spectrum. We have chosen a set of four nuclei which are very important from an experiment point of view in ongoing experiments.

The energy distribution of hep neutrinos is approximated by Fig. 1. This figure shows the energy spectrum of these neutrinos, $f(E_\nu)$, that is predicted by the standard solar model and normalized to unity as $\int f(E_\nu)dE_\nu = 1$.

The analytical expression which fits to the above energy distribution $f(E_\nu)$ of hep neutrinos is easily estimated by using appropriate program and in a very good approximation, this energy spectrum (continuum red line) is:

$$f(X) = \alpha_0 + \alpha_1 X + \alpha_2 X^2 + \alpha_3 X^3 + \alpha_4 X^4 + \alpha_5 X^5 \tag{9}$$

where

$\alpha_0 = 1 \cdot 10^{-5}$, $\alpha_1 = -2 \cdot 10^{-5}$, $\alpha_2 = 42 \cdot 10^{-4}$, $\alpha_3 = -44 \cdot 10^{-5}$, $\alpha_4 = 1 \cdot 10^{-5}$, $\alpha_5 = -2.6641 \times 10^{-9}$.

Our main goal of such efforts is to calculate the folded (convoluted) total cross sections of neutrino in nucleus reactions,$\sigma(E_\nu)$ given by various nuclear models. Currently we employed QRPA results for the total cross sections, for ^{16}O, ^{40}Ar, ^{56}Fe and ^{98}Mo nuclei and using the energy spectrum distribution for these channels: the coherent channel, $\langle\sigma_{coh}\rangle$ and the incoherent channel for various components of the hadronic current operator.

The results will be published elsewhere [11].

5 Summary and Conclusions

In the present work we adopt the most recent LUNA experimental data for the nuclear cross-section S-factor in order to update solar neutrino fluxes (Φ) for the p-p chain and compare with those obtained by previous theoretical solar models. We find that, our updated Φ_{pp} and Φ_{pep} are slightly improved from previous $\nu-$ fluxes while the $\Phi_{^7Be}$, $\Phi_{^8B}$ are appreciably improved over the previous models [8][12].

As a byproduct we computed lifetimes for the CNO nuclei using improved radiative opacities and element abundances and we compare our results with lifetimes obtained by other solar models. We conclude that the lifetimes are not significantly affected by the choice of heavy-element abundances or radiative opacities.

Currently we perform calculations for folded total cross sections of neutrino-nucleus reactions for four nuclei. The study of total cross sections in neutrino-nucleus reactions is of great importance in neutrino detection in particular for nuclear targets used in the existing neutrino detectors and promising nuclear isotopes proposed to be used as neutrino detection targets. Results will be published soon.

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