The Role Played by Plasma Waves in Stabilizing Solar Nuclear Fusion

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Since the wave function of two-scattering protons has been used for that of diproton or helium-2 in the conventional analysis with Fermi theory, the probability for a diproton to form a deuteron via a β^+-decay has been extremely under calculated. This implies that the rareness of β^+-decay in diprotons is not rare enough to inhibit the solar nuclear fusion. To meet the observed rate of solar nuclear fusion, the core of the Sun must involve another significant physical effect to inhibit solar nuclear fusion. This study finds that plasma waves can play this role, because they significantly reduce the electric permittivity of the core plasma and thus extremely raise the Coulomb barrier or shift the Gamow peak to a higher energy of particles. It is shown that, if the frequency of plasma waves that are globally generated in the core plasma of turbulences is about 1.28 times the plasma frequency, the Sun can have the actual fusion rate or shine on at the currently observed luminosity. Therefore, in addition to the quantum tunneling effect and rareness of β^+-decay, plasma waves can also play an essential role in the solar nuclear fusion and power emission. The result of this study may also give implications to supernova explosion, missing solar neutrino, and plasma nuclear fusion in laboratory.

1 Introduction

The Sun is a giant natural fusion reactor [1]. It smashes about 3.6×10^{38} hydrogen nuclei or protons per second to produce helium nuclei or α-particles, while releasing nuclear power of 3.85×10^{26} W. This nuclear fusion process occurring in the core of the Sun has been comprehensively investigated for many decades based on the well-developed stellar nucleosynthesis and quantum physics. It is well known that, in the dense and hot core of the Sun with ∼1.5 keV (or $\sim 1.67 \times 10^7$ K) temperature and Boltzmann-Maxwell's distribution of the core's total 1.2×10^{56} protons, there should not be any proton able to overcome the 820 keV (or 9.5×10^9 K) Coulomb barrier to make the fusion reactions occur.

According to Gamow's quantum tunneling probability [2] however, the energy region where nuclear reactions are most like ly to occur (i.e. the Gamow peak) is around 10^8 K. This allows one part per million of the core's total 1.2×10^{56} protons to penetrate the Coulomb barrier. With this probability of barrier tunneling or penetration, the high ion-collision frequency of 20 terahertz means that the core of the Sun fuses all its protons within the order of only microseconds (i.e. a rate of 10^{63} s^{-1}, 25 orders of magnitude higher than the actual reaction rate) and thus would instantaneously explode. It is generally believed that the major reasons why the Sun does not instantaneously blow up are (1) the difficulty of double proton (also called diproton) formation (estimated to be lowered only by $\sim 10^{-6}$ according to the Gamow tunneling probability), (2) the rareness of β^+-decay from diprotons (needed to be lowered by $\sim 10^{-25}$ according to the Sun's actual luminosity) and (3) the squeezing of the Sun's strong gravity.

However, in the conventional analysis and calculation of the Fermi theory of the β^+-decay, the significant wave function of two-scattering protons was usually used for the inefficient wave function of the diproton outside the potential energy well [3]. This is not physical and greatly weakens the wave function of the diproton inside the potential energy well, so that leads to the probability for a diproton to form a deuteron via a β^+-decay to be extremely under calculated [4]. In other words, the rareness of β^+-decay in diprotons may not be rare enough to inhibit the solar nuclear fusion or lower the fusion rate by 25 orders of magnitude, in order to stop the Sun's instantaneous explosion and have the currently observed luminosity. The quantum tunneling effect allows many diprotons formed in the Sun's core, but the probability for a diproton to form a deuteron via a β^+-decay may not be lower than that for a diproton to separate back to two protons by 25 orders of magnitude. Observations have only given an upper bound that a diproton (or helium-2 nucleus) gets β^+-decay by less than one per ten thousands, i.e. < 0.01% [5].

In this paper, we propose a new mechanism of inhibition that can significantly reduce the fusion reaction rate and thus effectively prevent the Sun from an instantaneous explosion. We suggest that the core of the Sun involves a significant physical effect or inhibitor called plasma oscillation or wave, which significantly reduces the electric permittivity of the core plasma. A significantly reduced electric permittivity will greatly raise the Coulomb barrier as well as efficiently lower the Gamow tunneling probability. These changes lead to greatly shift the Gamow peak to the region of higher energies of particles. Quantitative study in this paper indicates that if the frequency ω of plasma oscillations or waves that are globally generated in the core plasma of turbulences is about 1.28 times the plasma frequency ω_p, the Sun can have the actual fusion rate or shine on at the currently observed luminosity.

Therefore, in addition to the quantum tunneling effect, the plasma oscillations may play also an essential role in the Sun's nuclear fusion and power emission. The quantum tunneling effect makes the fusion to occur, while the plasma oscillations in association with the weak β^+-decay of diprotons guarantees that the Sun will not explode. We also suggest that a supernova explosion occurs when plasma oscillations in the core of a star at the end of its life are significantly weakened in intensity or changed in frequency, that causes the heavy ion fusion to be significantly speeded up and the huge amount of energies and neutrinos to be instantaneously emitted. The result of this study also gives important implications to plasma nuclear fusion in laboratory and the solar neutrino missing problem.

2 Coulomb barrier and solar nuclear power emission

The measurement of power emission indicates that the luminosity of the Sun at present is about 3.85×10^{26} W, which can be calculated from

$$L_\odot = 4\pi R^2 \sigma T^4, \tag{1}$$

where $R = 7 \times 10^8$ m is the radius of the Sun, $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4) is the Stefan-Boltzmann constant, and $T = 5778$ K is the surface temperature of the Sun. At this luminosity, the Sun's gravitational energy, determined by

$$U = \frac{3GM^2}{5R} \simeq 2.3 \times 10^{41}\ \text{J}, \tag{2}$$

can only let it shine about $U/L_\odot \sim 19$ million years, which is the thermal or Kelvin-Helmholtz timescale determined by $K/L_\odot$ and is much shorter than the actual Sun's lifetime. Here $G = 6.67 \times 10^{-11}$ N m^2/kg^2 is the gravitational constant, $M = 1.99 \times 10^{30}$ kg is the mass of the Sun, K is the internal energy or the total kinetic energy of particles in the Sun, determined by

$$K = \frac{3}{2} k_B N T_{\text{core}} \simeq 4.1 \times 10^{41}\ \text{J}, \tag{3}$$

with $k_B = 1.38 \times 10^{-23}$ the Boltzmann constant, $N = M/m_p$ the total number of protons within the Sun, $m_p = 1.67 \times 10^{-27}$ kg the mass of the proton, and $T_{\text{core}} = 1.67 \times 10^7$ K the temperature of the core of the Sun. It should be noted here that the hot core of the Sun is about 1/3 of its diameter or 1/10 of its mass, which means that the internal energy of the Sun should be several times less than that given by (3).

The total number of protons in the core of the Sun is given by

$$N_0 = \frac{1}{10}\frac{M}{m_p} \sim 1.2 \times 10^{56}, \tag{4}$$

or number density to be $n_0 \sim 2.2 \times 10^{30}$ m^{-3}. It is the number or number density of protons available for fusion and the Sun should be mainly powered by nuclear fusion. According to nuclear physics, every time four protons are fused to form one helium, the reactions produce two neutrinos, two positrons, and two photons, and release in total a net energy of $E_{4p} \sim 27$ MeV from the deficit of ~3% masses of four protons. The energy from the fusion of all protons in the core of the Sun, calculated by

$$E = \frac{1}{10}\frac{M}{4m_p} E_{4p} \simeq 1.3 \times 10^{44}\ \text{J}, \tag{5}$$

can run the Sun at the present rate of emission for about 10 billion years. On the other hand, to have the present energy emitting rate, the Sun needs to fuse its protons at a rate of about

$$\frac{dN_0}{dt} = \frac{4L_{Sun}}{E_{4p}} \simeq 3.6 \times 10^{38}\ \text{s}^{-1} \tag{6}$$

protons in one second.

In order to fuse protons, the extremely high Coulomb barrier between them, determined by

$$U_C = \frac{q_p^2}{4\pi\epsilon_0 d_p} \simeq 8.2 \times 10^2\ \text{keV or } 9.5 \times 10^9\ \text{K}, \tag{7}$$

must be overcome [6]. Here $q_p = 1.6 \times 10^{-19}$ C is the proton's electric charge (equal to the fundamental unit of charge e), $\epsilon_0 = 8.85 \times 10^{-12}$ C^2/(m^{2}N) is the electric permittivity constant in free space, and $d_p = 1.76 \times 10^{-15}$ m is the diameter of a proton. Since the average kinetic energy of protons in the Sun's core with temperature 1.67×10^7 K, $K = (3/2)k_B T_{core} = 2.16$ keV, is about 383 times lower than the Coulomb barrier between protons, and it must be very hard to have protons to be able to climb over the Coulomb barrier. According to the Boltzmann-Maxwellian distribution function [7, 8], we have the number of protons with velocity in the range v - v+dv to be given by

$$dN = N_0 \left(\frac{m}{2\pi k_B T}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2k_B T}\right) dv, \tag{8}$$

or with energy in the range of E - E+dE to be given by,

$$dN = N_0 \frac{2\pi}{(\pi k_B T)^{3/2}} \sqrt{E} \exp\left(-\frac{E}{k_B T}\right) dE. \tag{9}$$

Here N_0 is the total number of all particles. Then, the number of protons with energy above the Coulomb barrier U_C can be found by integrating the function (9) with respect to the energy (E) in the range from U_C to infinity as

$$\begin{aligned} N_C &= N_0 \int_{U_C}^{\infty} \frac{2\pi}{(\pi k_B T)^{3/2}} \sqrt{E} \exp\left(-\frac{E}{k_B T}\right) dE \\ &= \frac{2N_0}{\sqrt{\pi}} \sqrt{\frac{U_c}{k_B T}} \exp\left(-\frac{U_c}{k_B T}\right) + N_0 \operatorname{erfc}\left(\sqrt{\frac{U_c}{k_B T}}\right). \end{aligned} \tag{10}$$

Considering the ion collision frequency in the hot core of the Sun to be calculated by

$$\nu_i = 4.8 \times 10^{-8} Z_i^4 \mu^{-1/2} n_i \ln\Lambda\, T_i^{-3/2}\ \text{s}^{-1}, \tag{11}$$

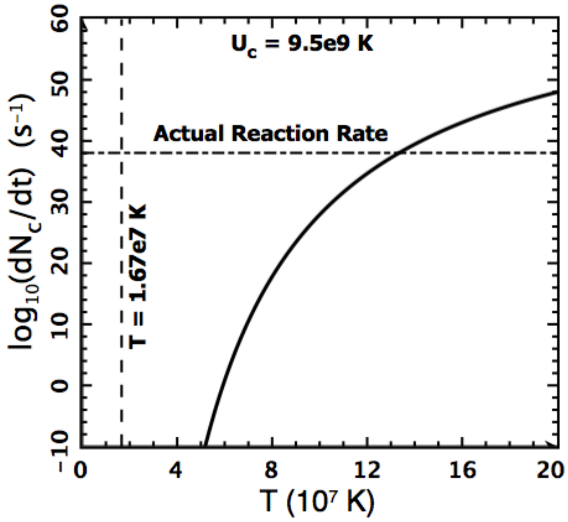

Fig. 1: The reaction rate of protons is plotted as a function of the Sun's core temperature in the case of without considering the quantum tunneling effect. The result indicates that no nuclear fusion can actually occur.

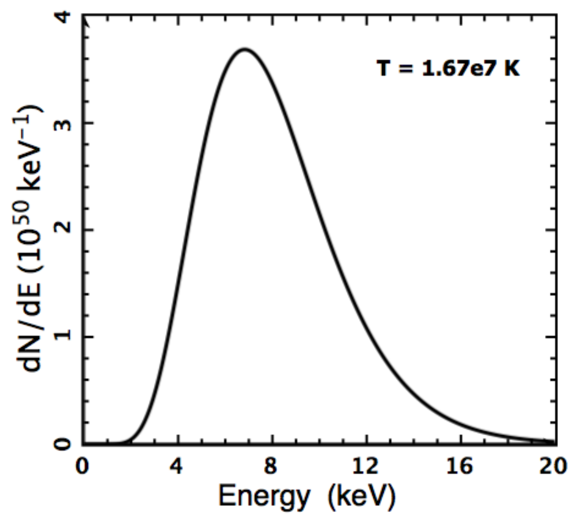

Fig. 2: Energy spectrum of protons that can penetrate the Coulomb barrier for fusion. The number of tunneling protons per unit energy in the core of the Sun is plotted as a function of the energy. The maximum is usually called the Gamow peak, which is located near the energy of about 7 keV.

where Z_i is the ion charge state, μ is the ion-proton mass ratio, n_i is the number of ions per cubic centimeter, $\ln\Lambda$ is the Coulomb logarithm with a convenient choice to be 10, and T_i is the ion temperature in units of eV. For protons in the Sun's core, the collision frequency can be $\nu_p \sim 2\times10^{13}$ Hz. The reaction rate of protons that can climb over the Coulomb barrier can then be estimated by

$$\frac{dN_C}{dt} = N_c\,\nu_p\,\mathrm{s}^{-1}. \tag{12}$$

Fig. 1 plots this reaction rate of protons as a function of the core temperature. It is seen that the reaction rate of the protons is about zero (many orders of magnitude less than 10^{-10} s^{-1}), so that no nuclear fusion occurs in the core of the Sun if the core temperature is equal to the conventional value T_{core} = 1.67×10^7 K. For the reaction rate of protons to be the actually observed rate of 3.6×10^{38} protons per second, the Sun's core temperature must be about 1.3×10^8 K or above. Therefore from classical physics, solar nuclear fusion will hardly occur.

3 Quantum tunneling effect on solar nuclear reaction

Quantum tunneling effect plays an essential role in solar nuclear fusion. According to the Gamow tunneling probability [2], given by

$$P_g = \exp\left(-\sqrt{\frac{E_g}{E}}\right), \tag{13}$$

one can determine the number of protons with energy between E and $E{+}dE$ that can tunnel through or penetrate the Coulomb barrier as

$$\begin{aligned} dN_g &= P_g dN \\ &= N_0\,\frac{2\pi}{(\pi k_B T)^{3/2}}\,\sqrt{E}\exp\left(-\frac{E}{k_B T}-\sqrt{\frac{E_g}{E}}\right)dE, \end{aligned} \tag{14}$$

where E_g is the Gamow energy determined by

$$E_g = 2m_r c^2(\pi\alpha Z_a Z_b)^2. \tag{15}$$

Here m_r is the reduced mass of the nuclei, c is the speed of light, Z_a and Z_b are the ionization states of the nuclei, and $\alpha = e^2/(2\epsilon_0 hc)$ is the fine-structure constant.

The distribution (14) for the number of tunneling protons with respect to the energy exhibits a maximum called the Gamow peak that has energy to be significant (about 120 times) less than the Coulomb barrier, so that the quantum tunneling effect greatly enhances the reaction rate in the core of the Sun. To see in more details the increase of the tunneling probability, we plot in Fig. 2 the Gamow peak for the Sun's core with temperature 1.67×10^7 K. The energy of the peak is around 7 keV and the height of the peak is around 3.7×10^{50} protons per keV.

Both the height and energy of the Gamow peak depend on the temperature of the Sun's core. Evaluating the extreme value of (14), we can obtain the energy of Gamow peak as a function of the core's temperature and other parameters or constants as the following implicit equation

$$1 - \frac{2E_p}{k_B T} + \sqrt{\frac{E_g}{E_p}} = 0. \tag{16}$$

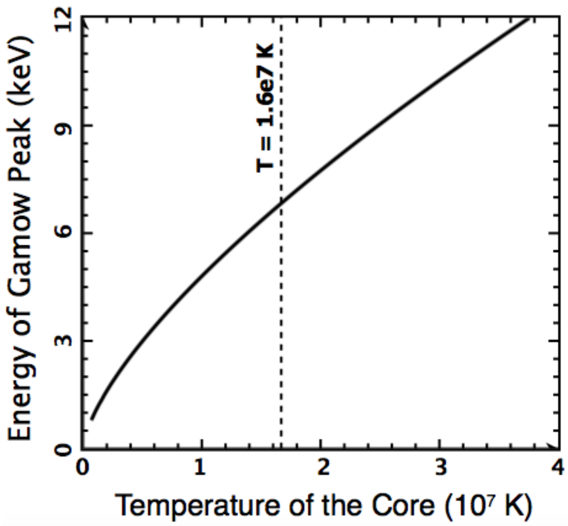

Fig. 3: The energy of the Gamow peak is plotted as a function of the temperature of the core.

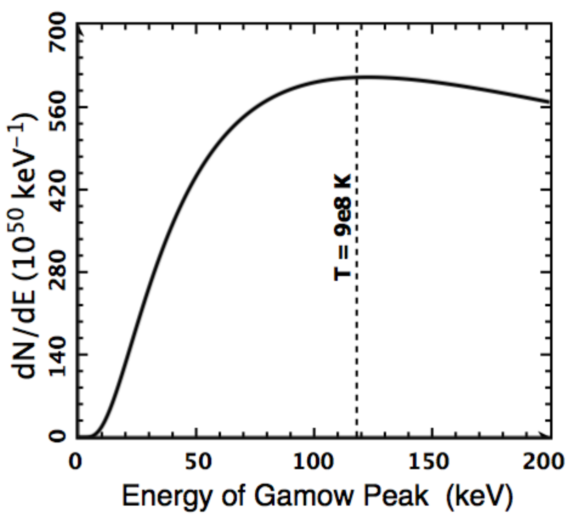

Fig. 4: The number of protons per unit energy is plotted as a function of the energy of the Gamow peak, which increases with the temperature core.

Substituting the energy of the Gamow peak (E_p) back into (14), we can determine the height of the Gamow peak as a function of the core's temperature and other parameters or constants. Fig. 3 plots the energy of the Gamow peak as a function of the temperature of the core. It is seen that the energy of the Gamow peak increases as the temperature of the core increases. The Gamow peak is at about 7 keV if the core temperature is 1.67×10^7 K and increases to 10 keV when the core temperature increases to 3×10^7 K. Fig. 4 plots the number of tunneling protons per unit energy (i.e. per keV) as a function of the energy of the Gamow peak, which increases as the temperature of the core increases as shown in Fig. 3. This further shows that the number of tunneling protons per unit energy reaches a maximum (~6×10^{52} keV^{-1}) when the energy of the Gamow peak is about 120 keV (or the temperature of the core is about 0.9 billion Kelvins). In the Sun's core temperature of 1.67×10^7 K, the energy of the Gamow peak is only 7 keV and the maximum number of tunneling protons is about 3.6×10^{50} keV^{-1}. Based on this peak of the maximum number of tunneling nuclei, we can find the maximum reaction rate as a function of the energy of the Gamow peak or the temperature of the core. This result may be important to optimize plasma fusion in the laboratory.

Then, the number of protons that can penetrate or tunnel through the Coulomb barrier can be found by integrating the function (14) with respect to the energy (E) in the range from zero to infinity as

$$\begin{aligned} N_g &= \int_0^\infty P_g dN \\ &= \lim_{E_2\to\infty} \int_0^{E_2} \frac{2\pi\sqrt{E}}{(\pi k_B T)^{3/2}} \exp\left(-\frac{E}{k_B T} - \sqrt{\frac{E_g}{E}}\right) dE. \end{aligned} \tag{17}$$

Multiplying N_g with the collision frequency, we obtain the reaction rate of nuclear fusion with the quantum tunneling effect as

$$\frac{dN_g}{dt} = N_g \nu_p. \tag{18}$$

To see the reaction rate quantitatively, we plot in Fig. 5 the reaction rate (18) as a function of the upper energy of the integration (E_2), which should approach infinity (or a value that is big enough, e.g. 30 keV). For the core of the Sun, the reaction rate saturates at $\sim 2 \times 10^{63}$ protons per second when the upper energy of the integration is $E_2 \gtrsim 30$ keV. This reaction rate is an order of magnitude 25 times higher than the actual reaction rate. Without a significant inhibitor to greatly slow down the reactions, the Sun should have instantaneously exploded.

4 Plasma oscillation effect on solar nuclear fusion

Plasma oscillations or waves can be considered as a great inhibitor for the solar nuclear reaction, because the dielectric constant of plasma with plasma oscillations or waves is given by [9]

$$\epsilon_r = 1 - \frac{\omega_p^2}{\omega^2}, \tag{19}$$

where ω_p is the plasma frequency defined by

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}, \tag{20}$$

and ω is the frequency of plasma waves generated in the core by the oscillations of free electrons. Eq. (19) indicates that

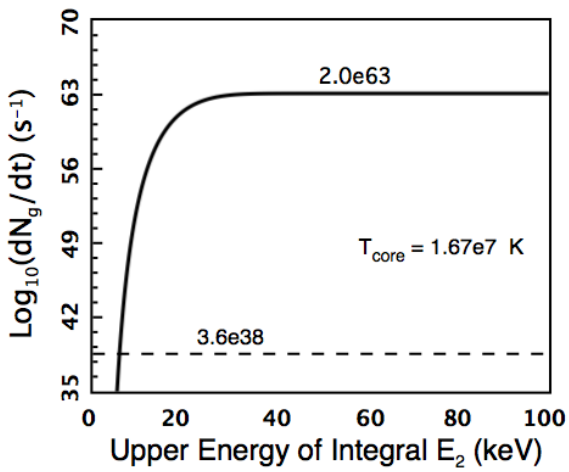

Fig. 5: The reaction rate of protons in the core of the Sun. The number of adequate collisions per second between protons is plotted as a function of the upper energy of the integration.

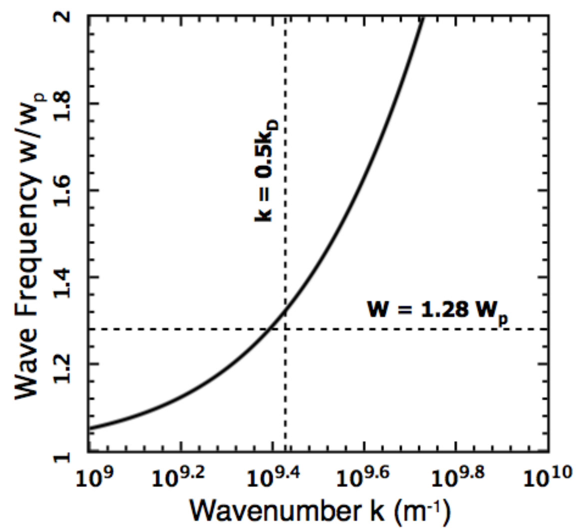

Fig. 6: The dispersion relation of the plasma Langmuir waves. The frequency of the waves is plotted as a function of the wavenumber. It is seen when the wavenumber is about half of the Debye wavenumber or wavelength is about the diameter or twice the radius of the Debye sphere.

plasma oscillations or waves can make the dielectric constant to be less than unity and hence raises the Coulomb barrier and increases Gamow energy or reduces quantum tunneling probability. Increases of both the Coulomb barrier and the Gamow energy can greatly reduce the fusion reaction rate.

There are several types of plasma waves that can be initiated by electron oscillations [10] such as electrostatic Langmuir waves [11] with the dispersion relation given by

$$\omega^2 = \omega_p^2 + 3k^2 v_{Te}^2, \tag{21}$$

where v_{Te} is the thermal velocity of electrons and k is the wavenumber. Fig. 6 shows the dispersion relation of the Langmuir waves by plotting the wave frequency as a function of the wavenumber. It is seen that the frequency is about 1.28 times the plasma frequency when the wavenumber is about $k \sim 10^{9.4} \sim 2.5 \times 10^9$ m^{-1}. It is about half of the wavenumber of blackbody radiation at the peak, $k_{bb} = T_{core}/(2.9 \times 10^{-3}) \sim 5.8 \times 10^9$ m^{-1} $\sim 2.3k$ and also half of the Debye wavenumber, $k_d = [n_e e^2/(\epsilon_0 k_B T_{core})]^{1/2} \sim 5.0 \times 10^9$ m^{-3} $\sim 2k$. In the core of the Sun, we have $\omega_p \sim 3.6 \times 10^{18}$ Hz, i.e. in the X-ray frequency range.

To see the plasma oscillation effect on the solar nuclear fusion, we plot in Fig. 7 the reaction rate (18) as a function of the upper energy of the integration in three cases with the frequencies of plasma oscillations or waves given by $\omega/\omega_p = 1.25, 1.28, 1.32$, respectively. For the core of the Sun with $\omega/\omega_p \sim 1.28$, the reaction rate saturates at $\sim 3.6 \times 10^{38}$ protons per second when the upper energy of the integration is $E_2 \gtrsim 80$ keV. This reaction rate is in magnitude about the order of the actual reaction rate. Slightly varying the frequency, we have a reaction rate quite different. In general, the higher the frequency of the plasma waves, the weaker the effect of plasma oscillations on the nuclear fusion is. It is an extremely efficient inhibitor of the solar nuclear fusion.

5 Discussions and conclusions

At the end of its life, a star runs out proton-proton fusion and thus varies the plasma oscillations, which causes this efficient inhibitor to be ineffective. With this reason, we suggest that supernova explosions may occur when plasma oscillations in the core of a star at the end of its life are significantly weakened in intensity or changed in frequency that cause the heavy ion fusion to be significantly speeded up and out of control and the huge amount of energies and neutrinos to be instantaneously emitted. This study of the role of plasma oscillation played in solar nuclear fusion provides us an alternative mechanism for supernova explosions, in addition to the previously proposed and developed models of supernova explosions driven by magnetohydrodynamtic (MHD) rotation [12], acoustic waves [13], neutrinos [14], and gravitational field shielding [15].

The plasma oscillations or waves with frequency about 1.28 times the plasma frequency can reduce the electric permittivity or the dielectric constant by a factor of one third in comparison with free space. The effective refractive index of plasma is given by $n = \sqrt{\epsilon_r} \sim 0.6$. Postulating the mass energy conversion in plasma by $E = mc^2/n^2$ leads to the deficit of 3% proton masses in fusion that can produce three times the nuclear energy. Then, having the same luminosity, the Sun only needs to fuse one third of the early suggested num-

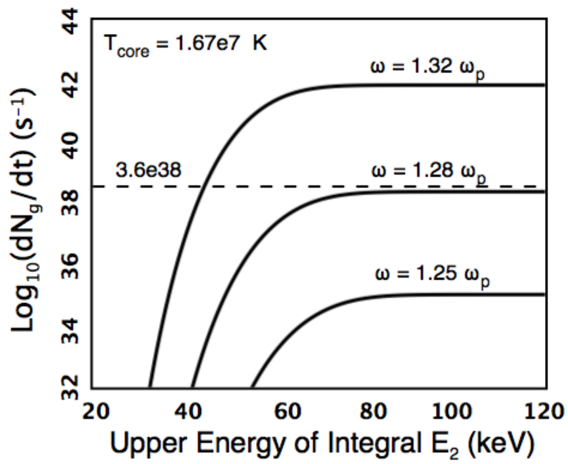

Fig. 7: The reaction rate of protons in the core of the Sun. The number of adequate collisions per second between protons is plotted as a function of the upper energy of the integration. Here the plasma oscillation effect on the reaction rate is included.

ber of protons, i.e. $\sim 1.2 \times 10^{38}$ protons per second. This result provides us an alternative of quantitatively explaining the missing two thirds of the solar neutrinos [16]. The Sun's lifetime is thus tripled, to be over thirty billion years.

Plasma oscillations with appropriate frequency of disturbances may also affect the nuclear reactions of plasma fusion in the laboratory. Above the plasma frequency ($\omega > \omega_p$), plasma oscillations would reduce the reaction rates and hence make the fusion hard to occur. Below the plasma frequency ($\omega < \omega_p$), however, plasma oscillations can lead to a negative dielectric constant, which switches the Coulomb interaction between nuclei to be an attractive force from a repulsive one. In this case, the Coulomb barrier disappears and nuclei fuse freely. Therefore, the result of this study also gives an important implication to plasma nuclear fusion in the laboratory. Regarding plasma fusion in the laboratory, the author has recently developed two new mechanisms: (1) plasma fusion at some keV with extremely heated ^{3}He ions or tritons [17–19]; (2) plasma fusion with Coulomb barrier lowered by scalar field [20].

As a consequence of this study, except for the conventional inhibitor of unlikely β^+-decay from diprotons, we find that plasma oscillations or waves can be an efficient inhibitor for the solar nuclear fusion, as it significantly reduces the electric permittivity of the core plasma and thus extremely raises the Coulomb barrier or shifts the Gamow peak to a higher energy of particles. When the frequency of plasma oscillations or Langmuir waves that are globally generated in the core plasma of turbulences is about 1.28 times the plasma frequency, the Sun can have the actual fusion rate or shine on at the currently observed luminosity. Therefore, in addition to the quantum tunneling effect, the weak β^+-decay, the plasma oscillations play also an essential role in the Sun's nuclear fusion and power emission.

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