Nuclear Fusion with Coulomb Barrier Lowered by Scalar Field

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The multi-hundred keV electrostatic Coulomb barrier among light elemental positively charged nuclei is the critical issue for realizing the thermonuclear fusion in laboratories. Instead of conventionally energizing nuclei to the needed energy, we, in this paper, develop a new plasma fusion mechanism, in which the Coulomb barrier among light elemental positively charged nuclei is lowered by a scalar field. Through polarizing the free space, the scalar field that couples gravitation and electromagnetism in a five-dimensional (5D) gravity or that associates with Bose-Einstein condensates in the 4D particle physics increases the electric permittivity of the vacuum, so that reduces the Coulomb barrier and enhances the quantum tunneling probability and thus increases the plasma fusion reaction rate. With a significant reduction of the Coulomb barrier and enhancement of tunneling probability by a strong scalar field, nuclear fusion can occur in a plasma at a low and even room temperatures. This implies that the conventional fusion devices such as the National Ignition Facility and many other well-developed or under developing fusion tokamaks, when a strong scalar field is appropriately established, can achieve their goals and reach the energy breakevens only using low-techs.

1 Introdction

The development of human modern society is inseparable from energy. Since the fossil fuels are nearing exhaustion and renewable energy sources cannot be sufficient, the best choice to thoroughly solve the future energy problems must be the nuclear fusion power. The most critical issue in nuclear fusion is the extremely high Coulomb barrier between positively charged nuclei, usually over hundreds of keV or billions of Kelvins [1]. From the quantum tunneling effect, which is derived from Heisenberg's uncertainty principle and the particle-wave duality, nuclei with kinetic energy of around ten keV or hundred million Kelvins, which is about some tens times lower than the actual barrier, are energetic enough to penetrate the barrier and fuse one another with sufficient probabilities. There are in general three possible ways for nuclei to overcome the Coulomb barrier between them and hence achieve the thermonuclear fusion: (i) heating both species of nuclei (or the entire plasma including electrons) to the needed temperature, (ii) heating only the minor species of nuclei to the needed temperature, and (iii) lowing the Coulomb barrier to the needed level. Figure 1 sketches a schematic of the three approaches for nuclei to overcome their Coulomb barrier that blocks them from fusion. A combination of two or all of the three approaches will certainly work more efficiently.

Since the middle of the last century, fusion scientists have been focusing on the approach (i), i.e. study of how to efficiently heat the entire plasma for nuclei to have such high energies and how to effectively control and confine such extremely heated entire plasma. The major types of heating processes that have been applied so far include the Joule heating by driving electric currents, the injection heating by injecting energized neutral beams, and the radio frequency (rf) heating by resonating nuclei or electrons with antenna-generated radio-frequency waves. The magnetic and inertial confinements are two major types of confinements. Although having made great progresses in the development of various kinds of fusion devices or tokamaks, human beings are still not so sure how many difficulties to be overcome and how far need to go on the way of seeking this ultimate source of energy from the nuclear fusion [2].

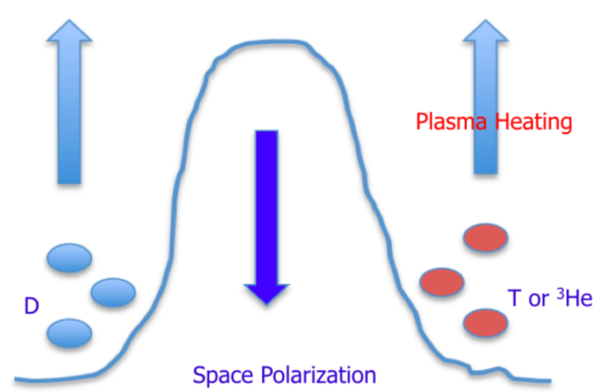

Fig. 1: A schematic of three ways for nuclei to overcome the Coulomb barrier. The first is the conventional approach that energizes both species of nuclei or the entire plasma including electrons to the needed energy for fusion. The second is the authors' recently developed approach that energizes the minor species of nuclei such as ^{3}He and T ions to the needed energy for fusion. And the third is the approach of this paper that lowers the Coulomb barrier to the needed level for fusion.

Recently, the authors innovatively proposed and further quantitatively developed the approach (ii), i.e. a new mechanism for plasma fusion at ten million Kelvins (MK) with extremely heated ^{3}He or tritium (T) ions [3–6]. This newly developed mechanism involves a two-stage heating process when an electric current is driven through a multi-ion plasma. The electric current first ohmically (or in the Joule heating process) heat the entire multi-ion plasma up to the order of 10 MK (or some keV), at which the electric resistivity in the plasma becomes too low for the electric current to be significantly dissipated further and the temperature of the entire plasma saturates at this level. When the electric current is continuously driven up to a critical point, the current-driven electrostatic H or D-cyclotron waves with frequency around twice as big as the ^{3}He or T-cyclotron frequency are excited, which can further heat ^{3}He or T ions via the second harmonic resonance to 100 MK and higher, at which the nuclear fusion between the extremely hot ^{3}He or T ions and the relative cold D ions (i.e. the D-^{3}He or D-T fusion) can occur. This new mechanism for plasma fusion at 10 MK with extremely heated ^{3}He or T ions can also greatly reduce the difficulty in controlling and confining of the plasma fusion.

In this study, we attempt to develop the approach (iii), i.e. to explore and find another new way towards this ultimate goal of using nuclear fusion energy through building an effective fusion reactor. Instead of only energizing the nuclei to the needed temperature, we lower the Coulomb barrier to the needed level. Towards this direction, there have been some analytical efforts done up-to-date by others for enhancing the quantum tunneling probability such as by catalyzing muons or antiprotons [7], driving cusps [8], spreading wave packets [9], forming coherent correlated states [10], screening with Bose-Einstein condensations [11], and so on. Rather than to catalyze the fusion, we will in this paper consider a scalar field to polarize the space or vacuum, in other words, to enhance the dielectric constant of the space or vacuum and hence reduce the electric potential energy or Coulomb barrier among nuclei. We will first calculate the effect of scalar field on the tunneling probability and the number of nuclei that can overcome the Coulomb barrier for fusion. We will then calculate the scalar field effect on the nuclear reaction rate of fusion. We will further investigate the physics and mechanism for a possible approach that generates a strong scalar field in labs to significantly lower the barrier and greatly enhance the quantum tunneling probability for nuclear fusion.

2 Lowering of the Coulomb Barrier by Scalar Field

Early studies have shown that the scalar field of a five-dimensional (5D) gravity can not only shallow the gravitational potential well by flattening the spacetime [12], or in other words, varying or decreasing the gravitational constant [13], but also lower the electric potential energy or Coulomb barrier among nuclei by polarizing the free space or vacuum [14, 15], or in other words, varying or increasing the dielectric constant [16]. From the exact field solution of 5D gravity [12, 17, 18], we can obtain the relative dielectric permittivity in the free space or vacuum polarized by a scalar field Φ as

$$\epsilon_r \equiv \frac{\epsilon}{\epsilon_0} = \frac{E_c}{E} = \Phi^3 \exp\left(\frac{\lambda - \nu}{2}\right), \tag{1}$$

where e^λ and e^ν are the $rr-$ and $tt-$ components of the 4D spacetime metric. This result implies that the electric potential energy or Coulomb barrier between nuclei is explicitly reduced by a factor of Φ^3. For a weak gravitational system such as in labs, because $e^\lambda \sim 1$, $e^\nu \sim 1$, we have $\epsilon_r = \Phi^3$. For a strong gravitational system such as nearby neutron stars or black boles, because $e^\nu \propto \Phi^{-2}$, we have $\epsilon_r \propto \Phi^4$. In quantum electrodynamics (QED) of particle physics, the vacuum polarization was calculated in accordance with the scalar Φ^3 theory [19]. The effect of scalar field vacuum polarization on homogeneous spaces with an invariant metric was obtained in [20].

The scalar field in the 5D gravity is a force field that associates with the mass and charge of a body and couples the gravitational and electromagnetic fields of the body. The scalar field associated with matter and charge in labs is negligible small, which may be able to be detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) that detected gravitational waves [21, 22]. For massive, compact, and, especially, high electrically charged objects such as neutron stars and black holes, we can have an extremely large scalar field. Although being one of the biggest unsolved mysteries in physics, the scalar field has been widely utilized to model and explain many physical phenomena such as Higgs particles, Bose-Einstein condensates, dark matter, dark energy, cosmic inflation, and so on.

Creatively, Wesson recently proposed a possible connection between the scalar field of 5D gravity and the Higgs scalar field of 4D particle physics [23]. The Higgs scalar field is an energy field that all particles in the universe interact with, and gain their masses through this interaction or Yukawa coupling [24, 25]. In the middle of 2013, CERN discovered the carrier of the Higgs scalar field, i.e. the Higgs boson, and thus confirmed the existence of the Higgs scalar field. On the other hand, according to the Ginzburg-Landau model of the Bose-Einstein condensates, the Higgs mechanism describes the superconductivity of vacuum. Therefore, the scalar field of the 5D gravity can be considered as a type of Higgs scalar field of 4D particle physics. The latter can be considered as a type of Ginzburg-Landau scalar field of Bose-Einstein condensates [26–28]. Then, that the scalar field of the 5D gravity can shield the gravitational field (or flatten the spacetime) and polarize the space or vacuum must imply that the Ginzburg-Landau scalar field of superconductors and superfluids in the state of Bose-Einstein condensates may also shield the gravitational field (or flatten the spacetime) and polarize the space or vacuum.

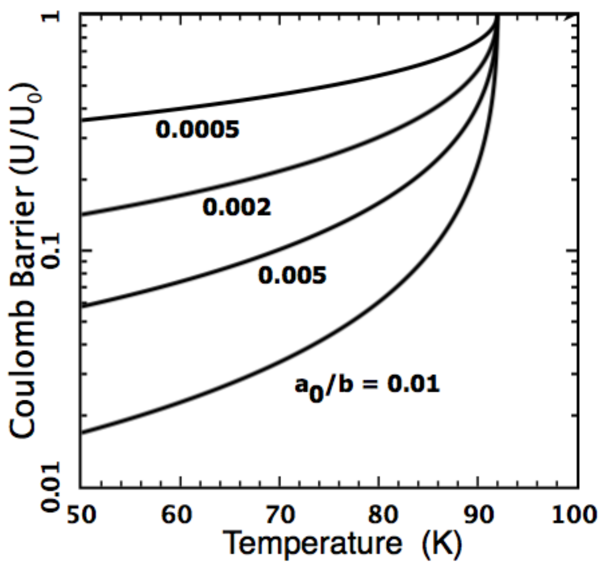

Fig. 2: The Coulomb barrier between two charges in the vacuum polarized by the Ginzburg-Landau scalar field of the Bose-Einstein condensate associated with the type II superconductor or superfluid, normalized by the barrier without the polarization, is plotted as a function of the temperature of the superconductor in the cases of different ratios of the two phenomenological constants a_0 and b.

In 1992, Podkletnov and Nieminen experimentally showed that a rotating disk of the type-II ceramic superconductor could shield Earth's gravity on a sample by a factor of $\sim 2-3\%$ [29]. If the disk is static, the shielding effect reduces $\sim$ 0.4% [30]. Recently, we have explained these measurements as the gravitational field shielding by the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with the type II ceramic superconductor disk [31], according to the 5D fully covariant gravity [12, 16, 18]. In the quantum field theory or quantum electrodynamics, many phenomena occurred or observed must be explained or described by relying on the physics of scalar field, for instances, the scalar field for cosmic inflation [32], the scalar field for dark matter or dark energy, and so on.

In the vacuum that is polarized by a Ginzburg-Landau scalar field of Bose-Einstein condensate associated with superconductor and superfluid, Φ_{GL}, the Coulomb barrier can be given by

$$U = \frac{U_0}{(1+\Phi_{GL})^3} \tag{2}$$

where

$$\Phi_{GL} = \sqrt{-\frac{a_0}{b}(T-T_c)} \tag{3}$$

with a_0 and b the two phenomenological constants, T and T_c the temperature and transition temperature of the condensate. For a quantitative study, we plot in Figure 2 the ratio of the Coulomb barrier in the vacuum that is polarized by the Ginzburg-Landau scalar field of Bose-Einstein condensates associated with a type II superconductor to that without polarization as a function of the temperature of the superconductor. In this plot, we have chosen the values $T_c = 92$ K and $a_0/b = 10^{-8}, 10^{-7}, 10^{-6}$ K^{-1} as done in [31, 33]. The vacuum polarization by a high magnetic field was measured by the Polarization of the Vacuum with Laser (PVLAS) using a superconducting dipole magnet of more than 8 Teslas magnetic field [34]. By a scalar field, a direct measurement of the vacuum polarization has not yet been conducted.

3 Penetrating of the Coulomb Barrier with Scalar Field

According to Gamow's tunneling probability [35] and Maxwell-Boltzmann's distribution function, one can find the relative number density of nuclei with energy from E to $E + dE$ in the plasma with temperature of T per unit energy that can penetrate the Coulomb barrier to be given by

$$\frac{dN}{dE} = \frac{2\pi}{(\pi kT)^{3/2}}\sqrt{E}\exp\left(-\frac{E}{kT}-\sqrt{\frac{E_g}{E}}\right), \tag{4}$$

where E_g is the Gamow energy determined by

$$E_g = 2m_r c^2(\pi\alpha Z_a Z_b)^2. \tag{5}$$

Here k is the Boltzmann constant, m_r is the reduced mass of nuclei, c is the light speed, Z_a and Z_b are the ionization states of nuclei, and $\alpha = e^2/(2\epsilon_0 hc)$ is the fine-structure constant. Considering the vacuum to be polarized by a scalar field (i.e. $\Phi > 1$), we modify the fine-structure constant by replacing ϵ_0 as $\epsilon = \Phi^3\epsilon_0$. It is seen that the scalar field can significantly reduce the Gamow energy and thus greatly increases the tunneling probability.

To see in more details for the increase of the tunneling probability, we plot in Figure 3 the Gamow peak in a D-T plasma first in the case of no scalar field (i.e. $\Phi = 1$). The plasma temperature has been chosen to be 10^7, 5×10^7, and 10^8 K, respectively. The result indicates, in a D-T plasma with density 2×10^{19} m^{-3} at 10^8 K, there are about two thousandth of total amount of nuclei to be able to tunnel through the barrier and participate in the fusion. Since the ion collision frequency in a fully ionized plasma can be estimated as $\nu_i = 4.8\times10^{-8} Z_i\sqrt{m_p/m_i}\ln\Lambda T_i^{-3/2} \sim 5$ Hz, for 10% of nuclei to react, the plasma must hold this temperature over 10 seconds. If the temperature is 5×10^7 or 10^7 K, then only around a few percent of or one in million nuclei can react within 10 seconds. Here we have used $\ln\Lambda = 6.8$ for ions.

With a scalar field, the tunneling probability will be significantly enhanced. Figure 4 plots the Gamow peak in a D-T plasma in the case of four different values of the scalar field (corresponding to the four lines in each panel, $\Phi = 1, 2, 10, 100$) and two different plasma temperatures of $T = 10^8$ K for the top panel and 10^7 K for the bottom panel. It is

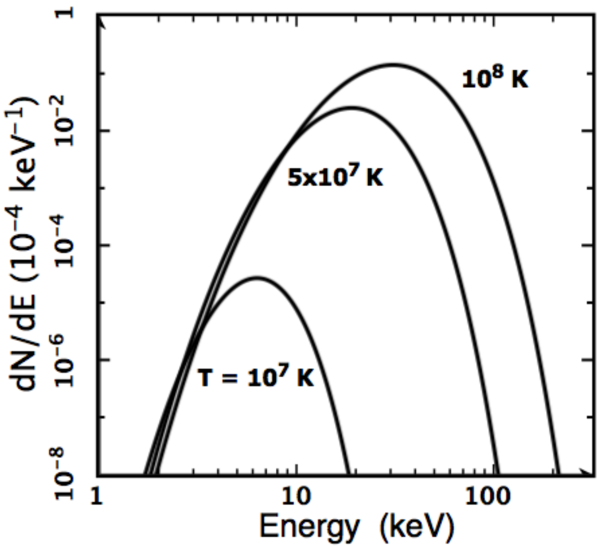

Fig. 3: The Gamow peak without a scalar field in a ^{2}H-^{3}H plasma with different temperatures or, in other words, the energy spectra of nuclei that are able to penetrate the Coulomb barrier for fusion. The relative number density of nuclei per unit energy with energy in the range from E to $E + dE$ is plotted as a function of the energy with temperature to be $T = 10^8, 5 \times 10^7, 10^7$ K, respectively. The maximum is usually called the Gamow peak [35].

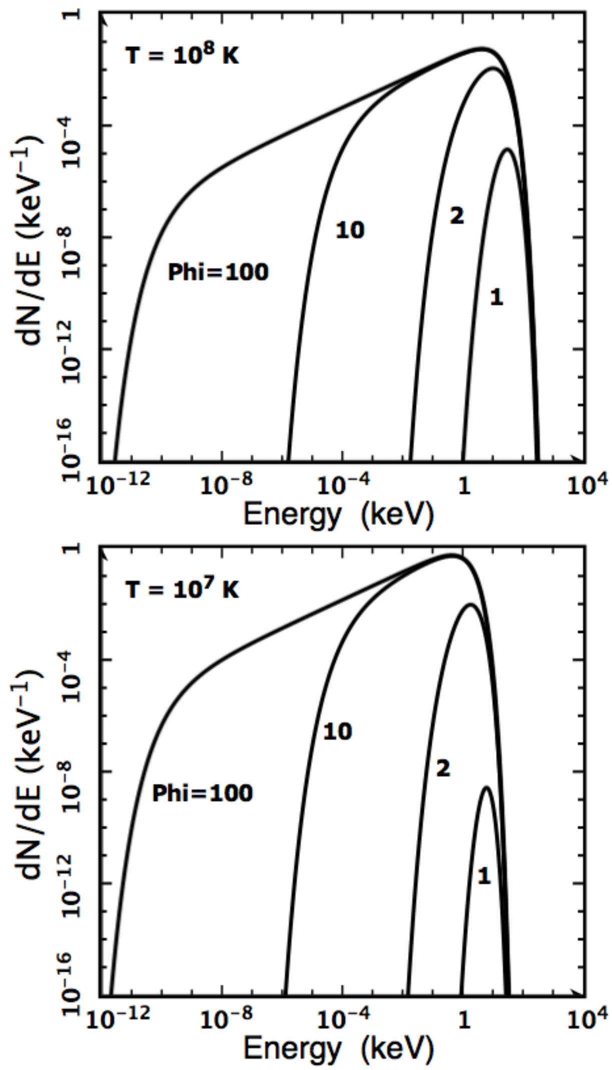

Fig. 4: The Gamow peak with a scalar field in a D-T plasma with different temperatures. This plots the energy spectra of nuclei that are able to penetrate the Coulomb barrier for fusion, i.e. the relative number density of nuclei per unit energy with energy in the range from E to $E + dE$ as a function of the energy with the scalar field $\Phi = 1, 2, 10, 100$ and temperatures to be $T = 10^8$ K for the top panel and 10^7 K for the bottom panel.

seen that when $\Phi > 2$ the number of nuclei that can tunnel through the barrier is enhanced by a factor of 1000 or greater at $T = 10^8$ K. At $T = 10^7$ K, the factor of enhancement can be 10^7 or greater. In addition, there are large amount of nuclei with extremely low energy can also tunnel through the barrier for fusion.

To see more details on the fusion of low energy nuclei, we plots the Gamow peak in Figure 5 for the D-T plasma with temperature equal to 10^6 K and 300K, respectively. In a 10^6 K plasma, the fusion can occur and be readily completed in seconds if $\Phi > 2$. At the room temperature, the nuclear fusion are also possible when $\Phi > 6$.

4 Fusion Rate

The fusion rate between two (i^{th} and j^{th}) species of ions, whose charge or ionization states are Z_i and Z_j, respectively, can be usually represented as [36–38]

$$R_{ij} = \frac{N_i N_j}{1 + \delta_{ij}} < \sigma v > \qquad (6)$$

where N_i and N_j are the number densities of the two species of ions, δ_{ij} is the Kronecker symbol, which is equal to the unity if the two species of ions are identical, otherwise, it is zero, v is the relative velocity, and σ is the cross section, determined by

$$< \sigma v >= \frac{6.4 \times 10^{-18}}{A_r Z_1 Z_2} \Phi^3 S \xi^2 \exp(-3\xi) \quad \text{cm}^3/\text{s}, \qquad (7)$$

with ξ to be defined as

$$\xi = 6.27 \Phi^{-2} (Z_i Z_j)^{2/3} A_r^{1/3} T^{-1/3}. \qquad (8)$$

Here we have considered the effect of space polarization on both the Coulomb barrier and the Gamow factor, simply by replacing $Z_i Z_j$ into $Z_i Z_j / \epsilon_r$ with $\epsilon_r = \Phi^3$ due to the space

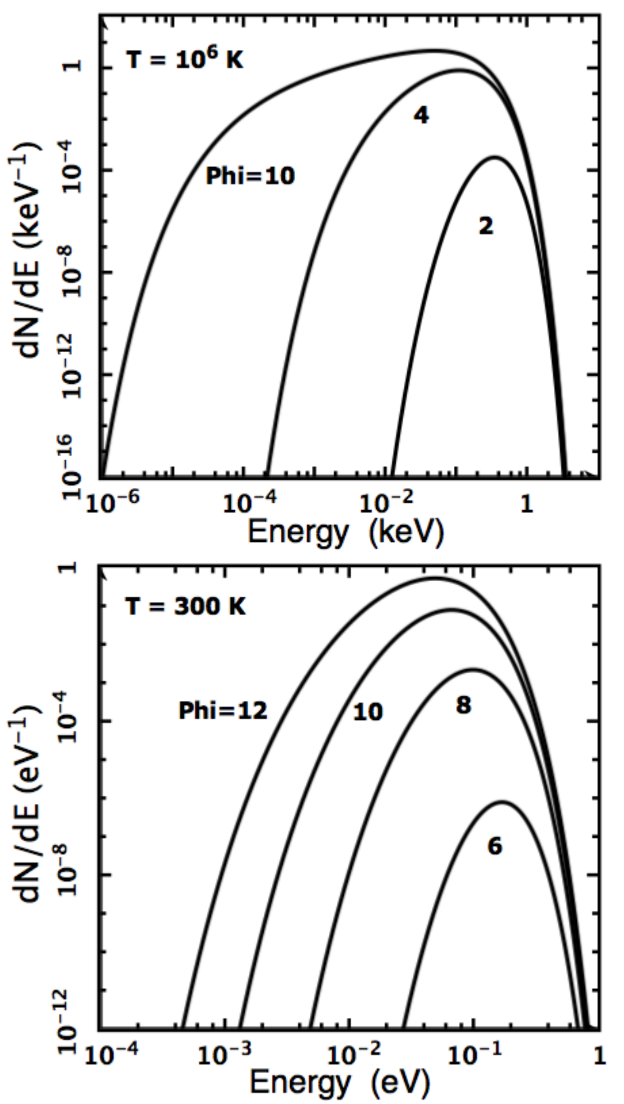

Fig. 5: The Gamow peak with a scalar field in a D-T plasma with different temperatures. This plots the energy spectra of nuclei that are able to penetrate the Coulomb barrier for fusion, i.e. the relative number density of nuclei per unit energy with energy in the range from E to $E + dE$ as a function of the energy with the scalar field $\Phi = 2, 4, 10$ and temperatures to be $T = 10^6$ K for the top panel. For the bottom panel, the scalar field is chosen to $\Phi = 6, 8, 10, 12$ and the temperature is chosen to be $T = 300$ K.

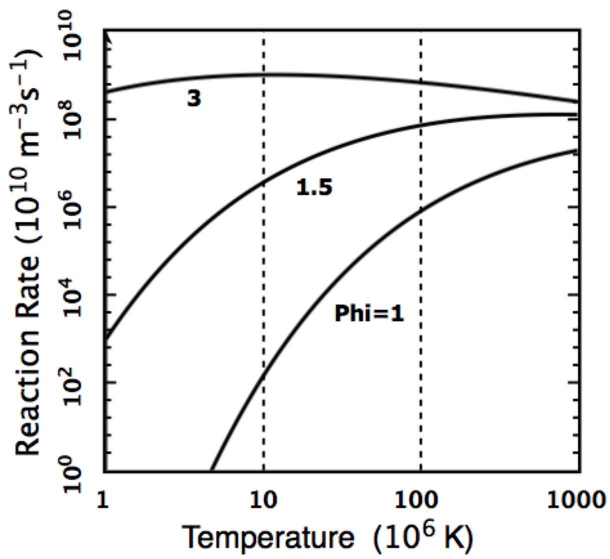

Fig. 6: The reaction rate of D-T fusion. The number of fusion reactions occurred in an unit volume (or m^3) of D-T plasma in one second is plotted as a function of the plasma temperature. Here the number densities of D and T nuclei are both chosen to 10^{19} m^{-3}, and the scalar field is chosen to 1, 1.5, and 3, respectively.

polarization by the scalar field Φ. In equations (7) and (8), the parameter S is the cross section factor, A_r is the reduced mass number, and T is the plasma temperature in keV. For the D-T fusion, we have $Z_i = Z_j = 1$, $A_r = 1.2$, and $S = 1.2 \times 10^4$ keV b.

To see how the scalar field to affect or enhance plasma fusion via the space polarization, we plot in Figure 6 the reaction rate of fusion as a function of the plasma temperature in the cases of the scalar field to be equal to $\Phi = 1, 1.5, 3$, respectively. It should be noted that the effect of scalar field comes from the difference of the scalar field from the unity or, in other words, there is no scalar field effect if $\Phi = 1$. The number densities of D and T nuclei are chosen to be $n_\mathrm{D} = n_\mathrm{T} = 10^{13}$ cm^{-3}. It is seen from the plot that the scalar field can significantly enhance the reaction rate of fusion. Without the effect of scalar field (i.e. $\Phi = 1$), the reaction rate of D-T fusion is about one thousandth m^{-3} s^{-1} (i.e. per cubic meters and per seconds) at temperature of about 10^8 K. With the effect of scalar field (i.e., $\Phi > 1$), the rate can be increased by 100 times to 10 percent m^{-3} s^{-1} when $\Phi = 1.5$ and by 1000 times to 100 percent m^{-3} s^{-1} when $\Phi = 3$.

5 Conclusion

We have developed a new mechanism for plasma fusion with the Coulomb barrier to be lowered by a scalar field. The result obtained from this study indicates, by polarizing the free space, a scalar field in associated with Bose-Einstein condensates can increase the electric permittivity of the vacuum and hence reduce the Coulomb barrier and enhance the tunneling probability. With a strong scalar field, nuclear fusion can occur in a plasma at a low and even room temperatures. Therefore, by appropriately generated a strong scalar field to polarize the space, we can make the conventional fusion devices to readily achieve their goals and reach the breakevens only using low-techs.

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