ЖЭТФ, 2018, том 154, вып. 5 (11), стр. 997–999

CONCEPTS FOR A DEUTERIUM–DEUTERIUM FUSION REACTOR

R. Onofrio*

Dipartimento di Fisica e Astronomia "Galileo Galilei", Università di Padova, Via Marzolo 8, Padova 35131, Italy

Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755, USA

Received April 15, 2018

Contribution for the JETP special issue in honor of L. P. Pitaevskii's 85th birthday

DOI: 10.1134/S0044451018110093

We discuss physical options for operating efficiently a deuterium–deuterium (D–D) fusion reactor, with known advantages with respect to the deuterium–tritium (D–T) reactors [1, 2]. The D–D cross-section in the interesting energy range for fusion is about two orders of magnitude smaller than the corresponding D–T cross-section, and therefore the requirements for igniting and self-sustaining the reaction are more demanding [3]. A possible solution is to look for ways to enhance the reactivity.

The usual comparison between D–D and D–T fusion rates relies on using Boltzmann energy distributions. However, situations can occur in which energy is injected into the plasma at a higher rate than the relaxation rate of the plasma itself. Under this circumstance, the high-energy tail of the distribution may be enhanced, generating large deviations from the Boltzmann distribution. These energy distributions, named κ-distributions, have been discussed since several decades in the context of low-density, low-temperature plasmas such as the solar wind [4]. The characterization of the κ-distributions requires the introduction of two parameters, the kinetic temperature, an effective temperature T_U such that the energy U per unit of particle can still be written as $U = 3k_BT_U/2$ as in the Boltzmann case, and the κ-parameter (with values in the $3/2 < \kappa < +\infty$ range). The energy probability density is expressed as [5]

$$P(E) = \frac{C(\kappa)}{(k_BT_U)^{3/2}} \frac{E^{1/2}}{\left[1 + \dfrac{E}{(\kappa - 3/2)k_BT_U}\right]^{\kappa+1}}, \quad (1)$$

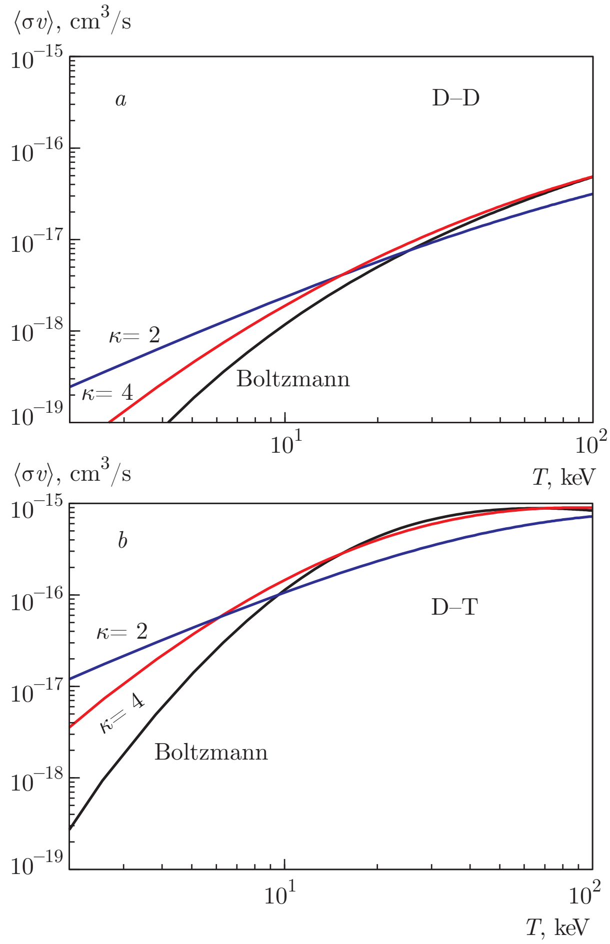
where

$$C(\kappa) = \frac{2\Gamma(\kappa+1)}{\pi^{1/2}(\kappa - 3/2)^{3/2}\Gamma(\kappa - 1/2)}.$$

The Boltzmann distribution is recovered in the case of $\kappa \to +\infty$ with the kinetic temperature of the κ distribution tending to the temperature T_{core} of the Boltzmann distribution interpolating its "core" distribution, i. e. the region of energies with the most probable population, $T_{core} = (1 - 3/2\kappa)T_U$. The specific value of κ is usually determined from a best fit of the observed energy distribution. Since most of the fusion reactions occur in the high-energy tail of the energy distribution, and the κ-distributions are characterized by a hard, power-law tails, it seems natural to evaluate the possible gain in reactivity for various fusion reaction by using κ-distributions with respect to the Boltzmann ones. We have used parameterized cross-sections for D–T and the two channels of the D–D fusion process from [6].

In the Figure we show the temperature dependence of the reactivities evaluated with averages over Boltzmann and κ-distributions for both D–D and D–T fusion reactions. There is a significant advantage in using κ-distributions, which should be beneficial also for the D–T reactors at relatively low temperatures, with reactivity gains of almost two orders of magnitude for temperatures in the few keV range. The Figure also shows that the κ-distribution is not consistently preferable to the Boltzmann distribution over the entire temperature range. Ongoing work mainly consists in developing kinetic models capable, for instance given the

* E-mail: onofrior@gmail.com



(Color online) Reactivities for D–D (a) and D–T (b) fusion processes averaged over Boltzmann energy distributions (black) and over two κ-distributed energies, $\kappa = 2$ (blue) and $\kappa = 4$ (red), in the 2–100 keV temperature range. Reactivities and temperatures in the two plots are expressed with the same scales allowing for an easier comparison. The D–D reactivity is obtained summing over both reaction channels, $D(d,p)T$ and $D(d,n)^3\mathrm{He}$

power level of neutral beam injection heating, of finding if the plasma energy may be expressed in terms of a κ-distribution, including predictions for the value of κ and its dependence upon the experimental parameters [7].

Two other possible routes to build efficient D–D reactors are also discussed in the paper.

A possible enhancement of the D–D reactivity may be achieved by exploiting vacuum polarization effects at the relatively higher temperatures at which a D–D reactor, if κ-distributions are not achieved, must necessarily work. The production of particle–antiparticle pairs is a process studied in finite temperature and density quantum field theory, with applications to a variety of research contexts ranging from astrophysics and cosmology to the observation of quark–gluon plasma at proton colliders (see for instance [8–10]). A detailed discussion of the effective potential between two charges separated by a sea of electrons and positrons at finite temperature and density is available in [11]. For temperatures low enough with respect to the production threshold of $2m_ec^2 \approx 1$ MeV and negligible chemical potential, an effective Yukawa potential has been evaluated [11], resulting in a Yukawa-like interaction ruled by a temperature-dependent Compton wavelength

$$\lambda_{eff} = \frac{\hbar}{2m_ec^2}\left(\frac{\pi m_e c^2}{2\alpha_{em}^2 k_B T}\right)^{1/4} \exp\left(\frac{m_e c^2}{2k_B T}\right), \qquad (2)$$

where α_{em} is the fine structure constant.

This may lead to a space-dependent weakening of the electrostatic repulsion between two nuclei. The screening due to the electron–positron plasma takes over the usual Debye screening above temperatures of practical interest. Unfortunately, in spite of the favorable scaling of the effective Yukawa range with temperature, the polarization effect is rather small. The effective Compton wavelength is still about four orders of magnitude larger than the average distance of minimum approach between the nuclei. On the other hand, the electron–positron plasma has a smaller inertia than the ions, so it can quickly adapt itself to the new situation creating a time-dependent barrier with an intermediate effectiveness, requiring a dynamical response approach. Alternative schemes to enhance the reactivity by replacing the electron with the muon in Eq. (2), and to provide the effective temperature of the $\mu^+\mu^-$ gas to be high enough are briefly discussed. One can create a situation in which $\lambda_{eff} \simeq r_T$. This is analogous to muon catalysis, and would require intersection points between the core of the confined plasma and an e^+e^- collider tuned at the $\mu^+\mu^-$ production peak.

Since a D–D reactor does not need a lithium blanket, one may design a direct conversion of the neutron energy into electrical energy, hopefully overcoming the limitation in efficiency of the traditional thermal cycles, of the order of 30 %. Recent developments in scintillating materials, decades-long experience with hadronic calorimeters, and progress in photovoltaic conversion may allow for an alternative scheme bypassing the thermal cycle while achieving comparable efficiency. A material scintillating with a light yield of 30 % has been recently discovered [12], and the third generation photovoltaic cells now under development are expected to reach 70 % efficiency [13]. Therefore, combining the two technologies, efficiencies of the order of 20 % seem already within reach. The maximum achievable power of the reactor in this approach seems limited by the radiation damage induced by neutrons in the calorimeter. Such a scheme can be feasible, in light of the maximum permissible neutron flux, for compact low and medium power fusion reactors, with applications to decentralized electricity production in regions requiring low power densities (for instance rural regions, and as a complement to intermittent, renewable power sources like wind and solar energy) but especially in the sector of maritime transport, with the prospect of a virtually unlimited range of the vessels and a much smaller environmental impact [14].

The full text of this paper is published in the English version of JETP.

REFERENCES

1. N. Mitchell and E. Salpietro, Nucl. Fusion **26**, 1246 (1986).
2. S. Zheng, D. B. King, L. Garzotti, E. Surrey, and T. N. Todd, Fusion Eng. Des. **103**, 13 (2016).
3. P. E. Stott, Plasma Phys. Control. Fusion **47**, 1305 (2005).
4. V. M. Vasyliunas, J. Geophys. Res. **73**, 2839 (1968).
5. D. C. Nicholls, M. A. Dopita, and R. S. Sutherland, Astrophys. J. **752**, 148 (2012).
6. H.-S. Bosch and G. M. Hale, Nucl. Fusion **32**, 611 (1992).
7. M. Salewski, B. Geiger, A. S. Jacobsen et al., Nucl. Fusion **58**, 036017 (2018).
8. P. Elmfors, D. Persson, and B.-S. Skagerstam, Phys. Rev. Lett. **71**, 480 (1993).
9. U. H. Danielsson and D. Grasso, Phys. Rev. D **52**, 2533 (1995).
10. J. I. Kapusta, *Finite-Temperature Field Theory*, Cambridge Univ. Press, Cambridge, England (1989).
11. J. Z. Kamiński, J. Phys. A **16**, 2587 (1983).
12. R. Hawrami, J. Glodo, K. S. Shah, N. Cherepy, S. Payne, A. Burger, and L. Boatner, J. Cryst. Growth **379**, 69 (2013).
13. G. Conibeer, Materials Today **10**, 42 (2007).
14. Z. Wan, M. Zhu, S. Chen, and D. Sperling, Nature **530**, 275 (2016).