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Screened effective quantum interaction potential for two-component plasmas

Yu V Arkhipov[1], **A B Ashikbayeva**[1], **A Askaruly**[1], **A E Davletov**[1], **D Yu Dubovtsev**[1], **I M Tkachenko**[2]
[1]IETP, Department of Physics and Technology, al-Farabi Kazakh National University, Almaty, Kazakhstan
[2]Departamento de Matematica Aplicada, Universidad Politécnica de Valencia, Valencia, Spain

Abstract. An effective pairwise interaction potential of charged particles which simultaneously takes into account quantum-mechanical and quantum-statistical effects in weakly and moderately non-ideal two-component plasmas at thermal equilibrium is constructed analytically as a screened Deutsch effective potential. The thermodynamic properties of two-component plasmas calculated using this interaction potential are compared to some available data.

Consider a two-component plasma where the number densities of electrons n_e and ions n_i comply with the quasi-neutrality condition $n_e = Zn_i$. An analytic effective potential is constructed within the random-phase approximation which is the screened Deutsch pseudopotential [1]:

$$\phi_{ab}(r) = \frac{Z_a Z_b e^2}{r}(1 - \exp(-k_{ab} r)) + \delta_{ae}\delta_{be}\frac{\ln 2}{\beta}\exp\left(-\frac{k_{ab}^2 r^2}{\pi \ln 2}\right) \quad (1)$$

where β is the system inverse temperature, k_{ab}^{-1} denotes the de Broglie thermal wavelength. Let a_B and a be the Bohr and Wigner-Seitz radii and let $f_e(p)$ and $f_i(p)$ represent the species' Fermi-Dirac distribution functions. Then long- and short wavelength asymptotic forms of the static dielectric function of a two-component plasma in the random-phase approximation (RPA) can be employed to screen (1) [2]:

$$\varphi_{ab}(r) = \frac{Z_a Z_b e^2}{r}(A\exp(-k_{ab} r) + B_1 \exp(-rK_1) - B_2 \exp(-rK_2)) \quad (2)$$

$$A = \frac{1}{\Delta}\left(1 - \frac{k_{ab}^2}{K^2}\right) \qquad B_{1,2} = \frac{C_{1,2}}{\mathrm{R}\Delta}\left(C_{1,2} - \frac{k_{ab}^2}{K^2}\right) \qquad K_{1,2} = K\sqrt{C_{2,1}}$$

$$\Delta = \frac{k_D^2}{k_{ab}^2} + \frac{k_{ab}^2 k_D^2}{k_q^4} - 1 \qquad C_{1,2} = \frac{1 \mp \left(1 - 4\frac{k_D^4}{k_q^4}\right)^{1/2}}{2} \qquad K = k_q^2/k_D$$

where $k_q^4 = \frac{16\pi e^2}{\hbar^2}(m_i n_i Z^2 + m_e n_e)$ and $k_D^2 = \frac{4}{\pi a_B}\left(\int_0^\infty f_e(p)dp + \frac{m_i}{m_e} Z^2 \int_0^\infty f_i(p)\, dp\right)$.

In moderately dense plasmas the radial distribution function $g_{ab}(r)$ and the partial static structure factors $S_{ab}(k)$ can be estimated in the spirit of the Debye - Hueckel theory as:

$$g_{ab}(r) = \exp(-\beta\varphi_{ab}(r)), \quad S_{ab}(k) = \delta_{ab} - \varphi_{ab}(k)\beta\sqrt{n_a n_b} \quad (3)$$

This permits to study the two-component plasma thermodynamic characteristics, namely, the dimensionless correlation energy and the equation of state (EOS):

$$u = \frac{2\pi\beta}{n_e+n_i}\int_0^\infty \sum_{a,b} n_a n_b \left(\phi_{ab}(r) + \beta\frac{\partial\phi_{ab}(r)}{\partial\beta}\right) g_{ab}(r) r^2 dr \quad (4)$$

$$P = P_{id} - \frac{2\pi}{3}\int_0^\infty \sum_{a,b} n_a n_b \frac{d\phi_{ab}(r)}{dr} g_{ab}(r) r^3 dr \quad (5)$$

with the exchange contribution to the Deutsch micropotential (1) taken into account. P_{id} is the quantum ideal-gas contribution. The corresponding results of the correlation energy and EOS for various values of the coupling parameter $\Gamma = \beta e^2/a$ are presented in Fig. 1:

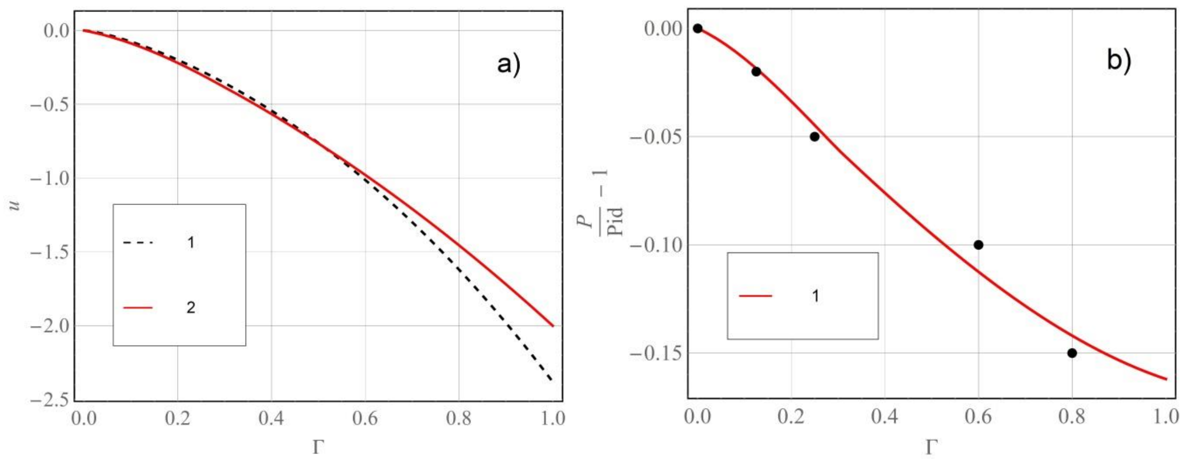

Figure 1(a, b). (a) Dimensionless correlation energy of a hydrogen plasma as a function of the coupling parameter at value of the degeneracy parameter $D = \beta E_F = 0.5$. 1 – [3], 2 – eq. (4); **(b)** EOS of a hydrogen plasma at value of the density parameter $r_s = a/a_B = 1$. 1 – eq. (5), circles – [4].

The effective pair interaction potential of charged particles in non-ideal plasmas which takes into account not only short-range and symmetry quantum effects, but also statistical quantum corrections has been obtained analytically. The thermodynamic functions of the hydrogen plasma have been evaluated and comparison with some theoretical and simulation data [3,4] has shown that the proposed effective potential is adequate for determination of static plasma characteristics.

References

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