Conditions (criteria) for existence of plasma

There are following conditions (criteria) for existence of plasma.

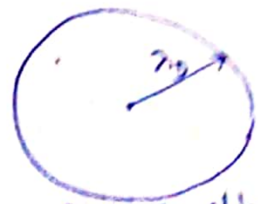
1. Quasineutrality :- According to Langmuir, an ionised gas is said to be plasma if Debye's length (λ_D) is very small compared with the linear dimension (L) occupied by the ionised gas.

So, for existence of plasma, $\boxed{\lambda_D << L}$

It is quantitative condition for Quasineutrality. It means an ionised gas will be quasineutral only when $\lambda_D << L$.

2. Collective behaviour :-

Let N_D = No. of plasma particles within Debye's sphere.



Debye's sphere

For existence of plasma, number of plasma particles within Debye's sphere should be much greater than one.

i.e, $\boxed{N_D >> 1}$ It is quantitative condition for collective behaviour. It means an ionised gas will have collective behaviour if $N_D >> 1$.

Determination of value of N_D in terms of plasma particle density (average) n_0 and absolute temperature T :-

Let n_0 = Average particle density of plasma

Now volume of Debye's sphere is given by

$$V = \frac{4}{3}\pi \lambda_D^3$$

Total number of plasm particles in the Debye's sphere will be

$$N_D = n_0 . V \Rightarrow N_D = n_0 . \frac{4}{3}\pi \lambda_D^3$$

$$\Rightarrow N_D = \frac{4}{3}\pi \left(\frac{\varepsilon_0 kT}{n_0 e^2}\right)^{3/2} \cdot n_0 \quad \because \lambda_D = \left(\frac{\varepsilon_0 kT}{n_0 e^2}\right)^{1/2}$$

$$\Rightarrow N_D = \left(\frac{4}{3}\pi \frac{\varepsilon_0^{3/2} \cdot k^{3/2}}{e^3}\right) \frac{T^{3/2}}{n_0^{1/2}} \quad \text{——— (1)}$$

Here $\varepsilon_0 = 8.85 \times 10^{-12} C^2/Nm^2$

$K = 1.38 \times 10^{-23} J/K$

$e = 1.6 \times 10^{-19} C$

Substituting these values in eqn (1) and after simplification, we get

$$\boxed{N_D = 1.38 \times 10^6 \cdot \frac{T^{3/2}}{n_0^{1/2}}} \quad \text{——— (2)}$$

Here $N_D = f(T, n_0)$

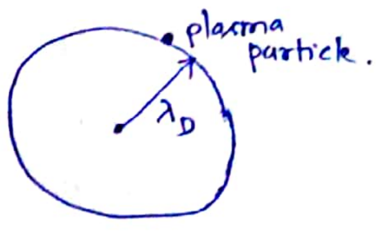
For collective behaviour, $N_D >> 1$

So, favourable condition for existence of plasma, temperature T should be large and average number density n_0 should be small.

3. plasma parameter (g) :- The ratio of potential energy of a plasma particle on the surface of Debye's sphere to translational Kinetic energy of the plasma particle on the surface of Debye's sphere, is known as plasma parameter. It is denoted by g.

$$g = \frac{\text{P.E of a plasma particle on the surface of Debye's sphere}}{\text{Translational K.E of the plasma particle on the surface of Debye's sphere}}$$

$$\Rightarrow g = \frac{U}{K} \quad \text{——— (3)}$$



P.E. of a plasma particle on the surface of Debye's sphere is

$$U = \frac{1}{4\pi\varepsilon_0} \cdot \frac{e^2}{\lambda_D} \quad \text{——— (4)}$$

From Maxwell-Boltzmann's Distribution, translational K.E of a plasma particle is

$$K.E = \frac{3}{2} kT \quad \text{——— (5)}$$

Using equⁿˢ (4) and (5) in equⁿ (3), we get

$$g = \frac{\frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{\lambda_D}}{\frac{3}{2}KT} = \frac{1}{4\pi\varepsilon_0}\cdot\frac{2e^2}{3KT}\cdot\frac{1}{\lambda_D}$$

$$g = \frac{1}{4\pi\varepsilon_0}\cdot\frac{2e^2}{3KT}\cdot\left(\frac{n_0 e^2}{\varepsilon_0 KT}\right)^{\frac{1}{2}} \qquad \because \lambda_D = \left(\frac{\varepsilon_0 KT}{n_0 e^2}\right)^{\frac{1}{2}}$$

$$\Rightarrow g = \left(\frac{1}{4\pi\varepsilon_0^{3/2}}\cdot\frac{2.e^3}{3.K^{3/2}}\right)\frac{n_0^{\frac{1}{2}}}{T^{3/2}}$$

$$\Rightarrow g = (\text{constant}).\frac{n_0^{\frac{1}{2}}}{T^{3/2}} \qquad \text{——— (6)}$$

Here plasma parameter $g \propto n_0^{\frac{1}{2}}$, $\propto T^{-3/2}$

This result is just opposite to for the result of N_D.

For a medium to be plasma,

$$\boxed{g << 1}$$

Thus for existence of plasma, value of plasma parameter (g) should be much less than 1.

For this average number density n_0 should be small and temperature T should be large which are same condition as for $N_D >> 1$.

Again $g << 1 \Rightarrow \frac{U}{K} << 1 \Rightarrow U << K$.

Thus for existence of plasma, kinetic energy (translational) of plasma particle on the surface of Debye's sphere should be much greater than P.E of the particle on the surface of Debye's sphere. (i.e. $K >> U$)

Near about 99.9% of universe is made up of plasma but plasma seldom exists on our planet i.e, on the surface of earth. Now we can understand, why plasma does not naturally exist on the surface of earth in terms of this plasma parameter. Actually on the surface of earth, $g << 1$ does not hold because n_0 is not small and T is not large. This is why plasma seldom exists on the surface of earth.

4. There is fourth criterion for the existence of plasma is that electromagnetic forces acting on the plasma particles should dominate over the forces due to collision.

Let ω = Frequency of plasma oscillation

τ = mean time between collisions with neutral atoms.

Then for existence of plasma,

$$\omega\tau > 1 \Rightarrow \frac{2\pi}{T} \cdot \tau > 1 \Rightarrow \boxed{\tau > \frac{T}{2\pi}}$$

where T = time period of oscillation of plasma particle.