Chemical and Biological Thermodynamics: Principles to Applications

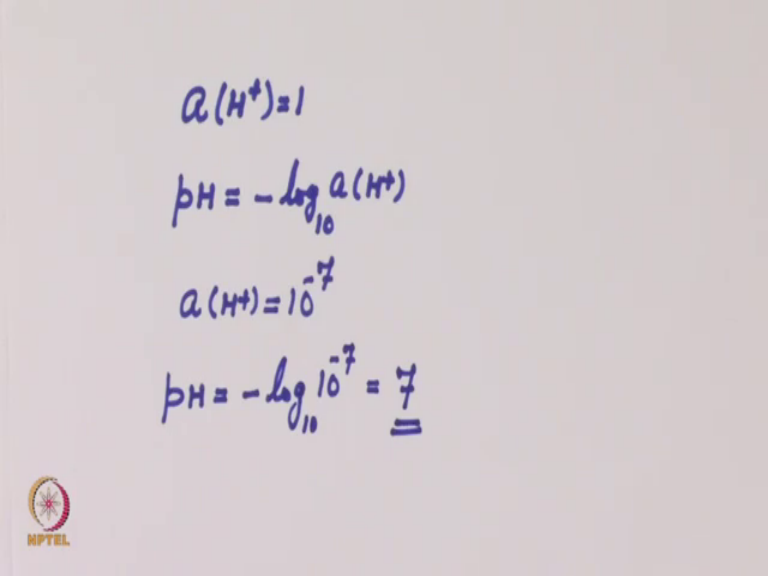
Prof. Nand Kishore
Department of Chemistry and Biochemistry
Indian Institute of Technology, Bombay

Lecture - 30
Biological standard states and pH

We have discussed the standard states. And we discussed standard state as the state of a substance, when it is in it is pure form temperature can be any and pressure has to be one bar; however, in biological systems the biological standard state is chosen in a different way. And we will discuss the details of biological standard states in this chapter.

So, in this lecture let us discuss; what is a biological standard state. The conventional standard state for hydrogen ion, if we were to write in solution will be when activity of hydrogen ion is equal to 1 that is the conventional standard state for hydrogen ion.

(Refer Slide Time: 01:38)



$$a(H^+) = 1$$

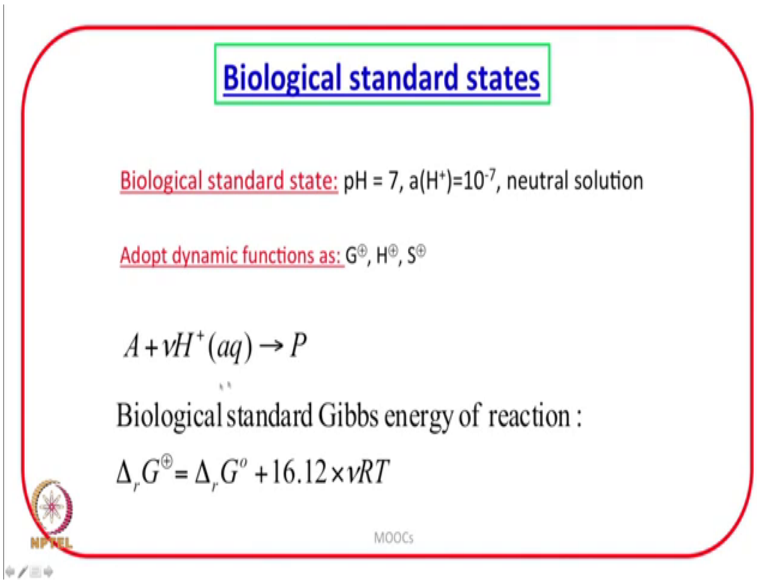
$$pH = -\log_{10} a(H^+)$$

$$a(H^+) = 10^{-7}$$

$$pH = -\log_{10} 10^{-7} = \underline{\underline{7}}$$

Now, if activity if activity of hydrogen ion is equal to 1, how do we define pH? PH office solution is minus logarithm base 10 activity of hydrogen ion most of the times we simply right this as concentration. Please remember that it should be activity not the concentration. You can only replace activity by concentration if the solution is very, very dilute. Now if we put activity of hydrogen ion here as 1; that means, pH will become 0 and that does not make sense.

(Refer Slide Time: 02:42)



Biological standard states

Biological standard state: pH = 7, a(H^+)=10^{-7}, neutral solution

Adopt dynamic functions as: $G^{\oplus}$, $H^{\oplus}$, $S^{\oplus}$

$$A + \nu H^{+}(aq) \rightarrow P$$

Biological standard Gibbs energy of reaction :

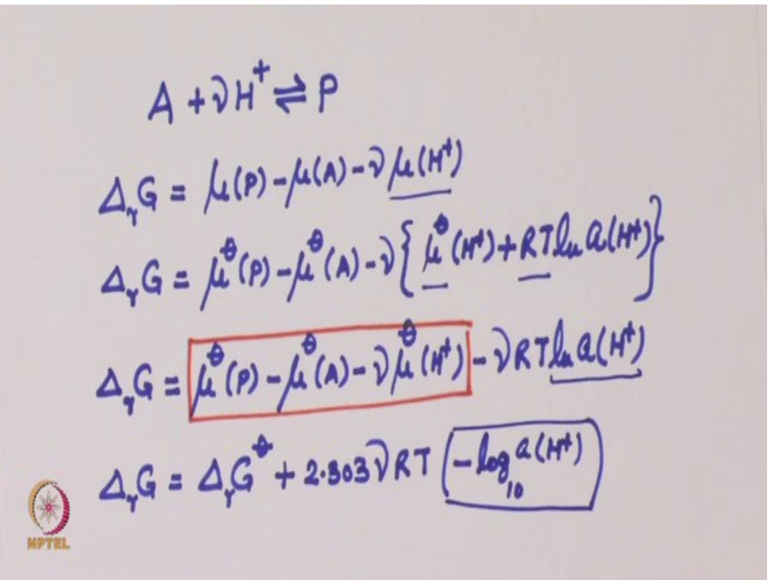
$$\Delta_r G^{\oplus} = \Delta_r G^{o} + 16.12 \times \nu RT$$

So therefore, biological standard state is defined in a different manner. Let us go to the slide. Biological standard state means, pH of the solution should be 7; that means, activity of hydrogen ion should be 10 raise to the power minus 7. So, if activity of hydrogen ion is equal to 10 raise to power minus 7, and we have discussed earlier that activities do not have any units. So therefore, we will not put any units with the activity. So therefore, pH will be equal to minus logarithm of base 10, 10 raise to the power minus 7, this is equal to 7. And that is what we call the biological standard state. PH 7 means the solution is neutral.

So therefore, we will also use a little different notations for the biological standard states. Let us go to slide. We will adopt dynamic functions as G with this special sign, H and S with these special signs. So, standard states, biological standard states for Gibbs energy for enthalpy for entropy, we will be representing by these symbols. We all understand the role of pH in biological systems. Because in biological systems the proton exchange of proton release or absorption of a proton usually happens. And therefore, the solutions are prepared in buffer, and buffer action is it will resist the changes in pH.

So, let us consider a reaction which involves the change of hydrogen ion or which involves the release or absorption of a proton.

(Refer Slide Time: 05:08)



$$A + \nu H^+ \rightleftharpoons P$$

$$\Delta_r G = \mu(P) - \mu(A) - \nu \underline{\mu(H^+)}$$

$$\Delta_r G = \mu^\ominus(P) - \mu^\ominus(A) - \nu\left\{\underline{\mu}^\ominus(H^+) + \underline{RT}\ln a(H^+)\right\}$$

$$\Delta_r G = \boxed{\mu^\ominus(P) - \mu^\ominus(A) - \nu\mu^\ominus(H^+)} - \nu RT\underline{\ln a(H^+)}$$

$$\Delta_r G = \Delta_r G^\ominus + 2.303\nu RT\boxed{-\log_{10} a(H^+)}$$

Let us consider this reaction A plus nu moles of H and this is in equilibrium or forming a product.

The usual way of writing reaction Gibbs energy which is actually a slope of Gibbs energy versus extent of reaction, we have earlier discussed that this is equal to the difference in chemical potentials of the product and reactors. So, it will be equal to chemical potential of P minus chemical potential of A minus mu times chemical potential of H plus. And it is these chemical potentials which will decide the sign of reaction Gibbs energy.

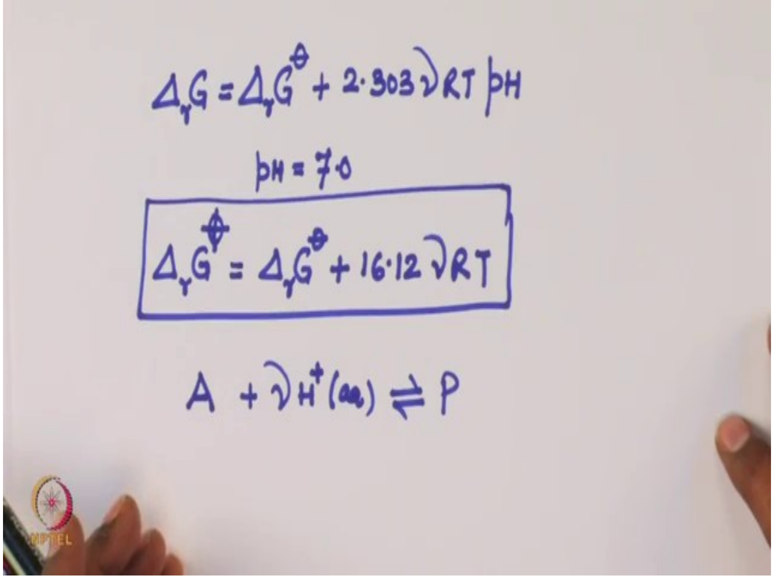
Now, let me assume a situation where A and P are in their standard states except H plus. I repeat let us assume a situation where A and P are in their standard states except H in that case delta r G will be equal to mu naught P minus mu naught A minus, this is the stoichiometric number. And in place of mu H naught, I will write mu naught H plus plus R T log activity of H plus. Because we know that mu is equal to mu naught plus R T log a, that we have discussed in one of the previous lectures. From this step to this step what I have said is, let A and P be in their standard states.

So, I will write their chemical potentials as their standard state chemical potentials. And I am not saying that let H plus be in the standard state let it be general under any condition. So, instead of mu I write mu naught plus R T log activity of H plus. Now I will combine all the standard state quantities. So, delta r G is equal to mu naught P minus mu naught A minus mu naught H minus nu R T log activity of H plus.

I will combine all these standard state quantities. And therefore, I have delta r G is equal to this is nothing but delta r G naught difference in the standard state chemical potentials, and minus log activity of hydrogen ion, let us write like this plus 2.303 nu R T minus log base 10 activity of hydrogen ion. I have written this as 2.303 into log base 10. And let us remember that this is equal to pH this is pH.

So, I will now write this equation as delta r G is equal to delta r G naught plus 2.303 nu R T into pH.

(Refer Slide Time: 10:03)



$$\Delta_r G = \Delta_r G^{\ominus} + 2.303\,\nu RT\,pH$$

$$pH = 7.0$$

$$\boxed{\Delta_r G^{\oplus} = \Delta_r G^{\ominus} + 16.12\,\nu RT}$$

$$A + \nu H^+(aq) \rightleftharpoons P$$

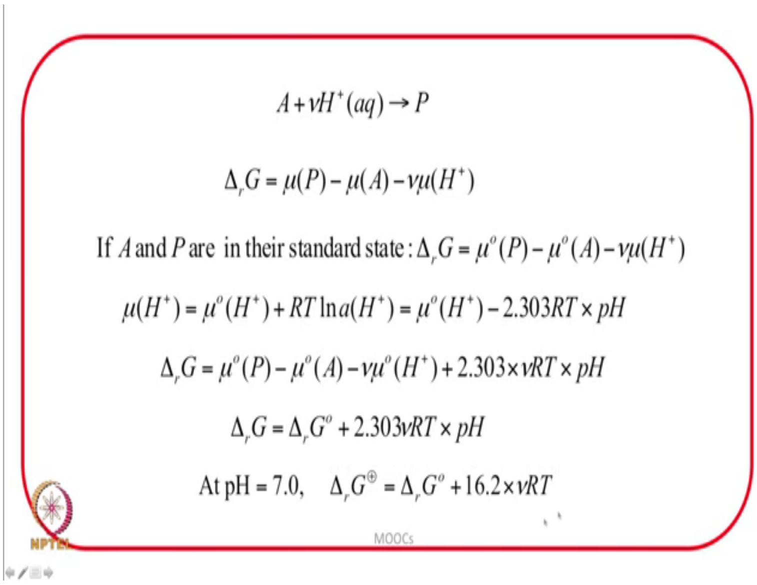
And when pH is equal to 7; that means, when we are talking about biological standard state, then 7 multiplied by 2.303 will give us a relation, but this now since we are talking about biological standard state is equal to delta r G naught plus this is 16.12 into nu R T, this is the equation that we derive.

Please note here since we are putting pH is equal to 7 therefore, I am writing this as the biological standard state reaction Gibbs energy. This is the thermodynamic standard state reaction Gibbs energy. Nu is the number of hydrogen ions produced or release, because our original reaction was A plus nu times H aquas it is in equilibrium with P that is what our original reaction was.

So obviously, when nu is equal to 0 when there is no proton released or absorbed then both these standard states will be equal standard state reaction Gibbs functions will be equal. And if there is a proton observed or proton released, then the biological reaction standard reaction Gibbs energy will be different than the normal thermodynamic re- standard reaction Gibbs energy. And in biological systems it is this which will determine whether the reaction will be exergonic or endergonic, because as I said most of the biological process is involved release or absorption of a proton.

Now, let us go to the slide for this reaction A plus nu H plus going to product we have developed this equation for the biological standard Gibbs energy of the reaction. This 16.12 comes from 2.303 into pH value of 7, and this equation can be used to get the value of biological standard Gibbs energy of reaction.

(Refer Slide Time: 13:30)



$$A + \nu H^{+}(aq) \rightarrow P$$

$$\Delta_r G = \mu(P) - \mu(A) - \nu\mu(H^{+})$$

If A and P are in their standard state : $\Delta_r G = \mu^{o}(P) - \mu^{o}(A) - \nu\mu(H^{+})$

$$\mu(H^{+}) = \mu^{o}(H^{+}) + RT\ln a(H^{+}) = \mu^{o}(H^{+}) - 2.303RT \times pH$$

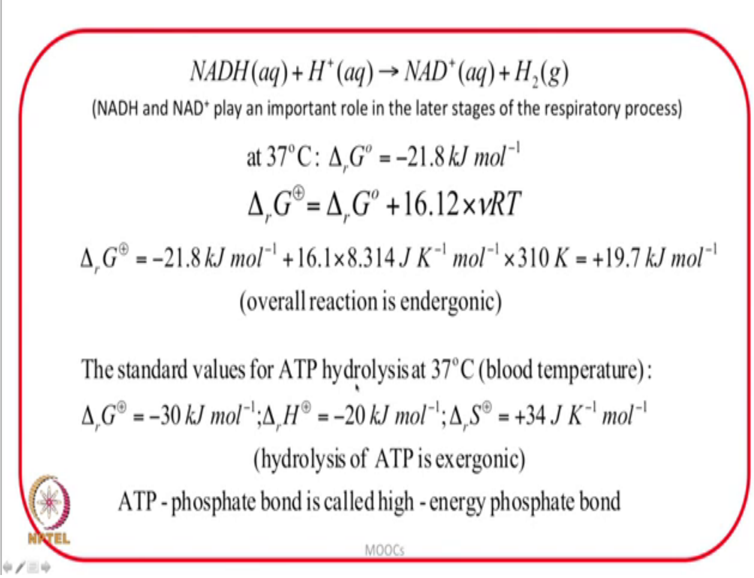
$$\Delta_r G = \mu^{o}(P) - \mu^{o}(A) - \nu\mu^{o}(H^{+}) + 2.303 \times \nu RT \times pH$$

$$\Delta_r G = \Delta_r G^{o} + 2.303\nu RT \times pH$$

At pH = 7.0, $\Delta_r G^{\oplus} = \Delta_r G^{o} + 16.2 \times \nu RT$

Now, let us once again considered this, and quickly go through the steps that we used. First we wrote the reaction Gibbs energy which is in terms of the chemical potentials. Then in the next step we consider P and A in their standard states except H. And then we used the definition of chemical potential for H plus and substituted into this equation. And we eventually got this result and at pH 7 this result converts into this expression for the biological standard state reaction Gibbs energy.

(Refer Slide Time: 14:28)



$NADH(aq) + H^+(aq) \rightarrow NAD^+(aq) + H_2(g)$

(NADH and NAD^+ play an important role in the later stages of the respiratory process)

at 37°C: $\Delta_r G^o = -21.8\,kJ\,mol^{-1}$

$$\Delta_r G^{\oplus} = \Delta_r G^o + 16.12 \times \nu RT$$

$\Delta_r G^{\oplus} = -21.8\,kJ\,mol^{-1} + 16.1 \times 8.314\,J\,K^{-1}\,mol^{-1} \times 310\,K = +19.7\,kJ\,mol^{-1}$

(overall reaction is endergonic)

The standard values for ATP hydrolysis at 37°C (blood temperature):

$\Delta_r G^{\oplus} = -30\,kJ\,mol^{-1}; \Delta_r H^{\oplus} = -20\,kJ\,mol^{-1}; \Delta_r S^{\oplus} = +34\,J\,K^{-1}\,mol^{-1}$

(hydrolysis of ATP is exergonic)

ATP - phosphate bond is called high - energy phosphate bond

Let us consider an example, nicotinamide adenine dinucleotide in the given reaction we have the reduced form of nicotinamide adenine dinucleotide NADH and NAD plus is the oxidized form and this is the reaction. There is a proton involvement, and both NAD NAD plus are biologically important molecules. An In fact, NAD and NAD plus play an important role in the later stages of respiratory process. Therefore this reaction is very, very important. At blood temperature that is 37 degree centigrade, the standard reaction Gibbs energy is minus 21.8 kilo joule per mol.

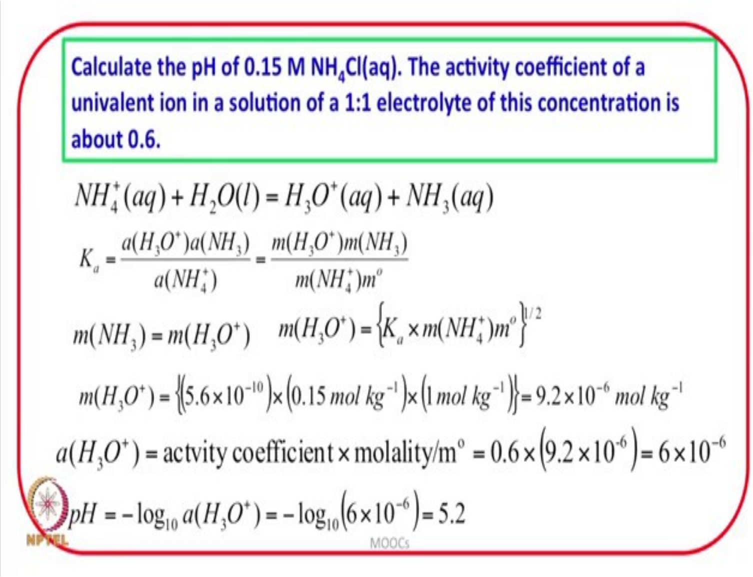
But here we will be interested in knowing the biological standard reaction Gibbs energy, which can be calculated from this reaction, this expression. We know the value of delta r G naught and we know how many protons are involved, is one only you substitute the value of r and t as seen in the next step, an overall value is plus 19.7 kilojoules per mol.

You see the biological standard reaction Gibbs energy is overall positive, overall positive means the reaction is endergonic, endergonic reactions are not spontaneous. Now let us take another example for ATP hydrolysis this is one example of a exergonic reaction. Again let us consider the blood temperature which is 37 degree Celsius.

The calculation suggest that the biological standard reaction Gibbs energy is minus 30 kilojoules per mole, minus 30 kilojoules per mole is a highly negative value; that means, the reaction is highly exergonic. Exergonic reaction means it can drive non spontaneous processes provided some enzymes are available which will catalyze those reactions, and also if we look at on the slide that the hydrolysis of ATP is exothermic in nature.

And entropy is also quite appreciable which is plus 34 joules per Kelvin per mole. Whenever you have a large value of entropy change; that means, the reactions are highly dependent upon temperature. Temperature is one of the factors which will affect the values of entropy change. And since this delta r G that is the biological standard reaction Gibbs energy is very negative and the hydrolysis of ATP thus we can label as highly exergonic, that is why this ATP phosphate bond is called high energy bond. The energy produced or the reaction is so highly exergonic that it can drive the other endergonic processes; it can drive the other non spontaneous processes.

(Refer Slide Time: 18:46)



Calculate the pH of 0.15 M $NH_4Cl(aq)$. The activity coefficient of a univalent ion in a solution of a 1:1 electrolyte of this concentration is about 0.6.

$$NH_4^+(aq) + H_2O(l) = H_3O^+(aq) + NH_3(aq)$$

$$K_a = \frac{a(H_3O^+)a(NH_3)}{a(NH_4^+)} = \frac{m(H_3O^+)m(NH_3)}{m(NH_4^+)m^o}$$

$$m(NH_3) = m(H_3O^+) \qquad m(H_3O^+) = \left\{K_a \times m(NH_4^+)m^o\right\}^{1/2}$$

$$m(H_3O^+) = \left\{(5.6\times10^{-10})\times(0.15\ mol\ kg^{-1})\times(1\ mol\ kg^{-1})\right\} = 9.2\times10^{-6}\ mol\ kg^{-1}$$

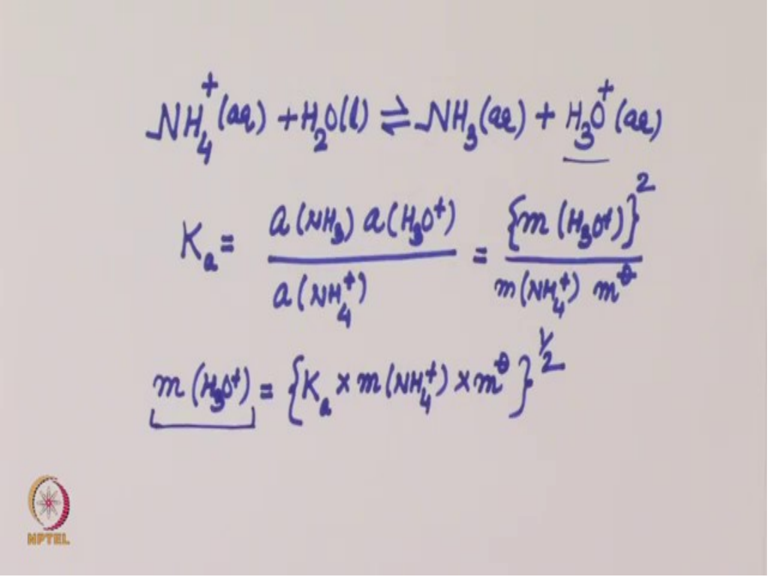
$$a(H_3O^+) = \text{actvity coefficient} \times \text{molality/m}^o = 0.6\times(9.2\times10^{-6}) = 6\times10^{-6}$$

$$pH = -\log_{10} a(H_3O^+) = -\log_{10}(6\times10^{-6}) = 5.2$$

Now, let us discuss another question on the pH, the question is calculate the pH of 0.15 molar ammonium chloride aquas, the activity coefficient of a univalent ion in a solution of 1 is to 1 electrolyte of this concentration is about 0.6. An easy question, we have to calculate the pH of ammonium chloride. And the concentration of ammonium chloride is given.

In the beginning of the lecture we define pH as negative log base 10 activity of hydrogen ion. What we have is ammonium chloride.

(Refer Slide Time: 19:56)



$$NH_4^+(aq) + H_2O(l) \rightleftharpoons NH_3(aq) + \underline{H_3O^+}(aq)$$

$$K_a = \frac{a(NH_3)\, a(H_3O^+)}{a(NH_4^+)} = \frac{\{m(H_3O^+)\}^2}{m(NH_4^+)\, m^\ominus}$$

$$\underbrace{m(H_3O^+)} = \{K_a \times m(NH_4^+) \times m^\ominus\}^{1/2}$$

Ammonium chloride means we have NH 4 aquas. And upon interaction with water it forms NH 3 aquas, plus you have H3O. So, this is the due to the proton release. NH 4 plus is weakly acidic. And In fact, we have in the question which is given to us has ammonium chloride. Chloride ion is not that appreciably basic moiety that it will affect the pH. Ammonium ion is very weakly acidic weekly acidic means the pH of the solution is going to be less than 7. And based upon this equation we want to calculate the concentration of H3O and if we know the concentration or molality of H3O plus then from the activity coefficient we can calculate the activity.

So, let us write down an expression for it is Ka which will be activity of ammonia activity of H3O plus activity of NH 4 plus, water we take as 1. An activity is equal to activity coefficient into molality. For pure ammonia this ammonia we will consider activity to be equal to it is molality. And for these the activity coefficients will cancel out.

So that means, in fact, in this expression we do not need to consider activity coefficient because these will cancel out assuming that the activity coefficients are same for those. So, I will write in terms of molality, molality of H3O plus square. Because the concentration is same it is 1 is to 1. So, molality's are equal divided by molality of NH 4 plus and I will also put m naught. M naught is one mole per kg because it is to be made dimensionless quantity. So therefore, I have molality of H3O plus will be equal to Ka into molality of NH 4 plus into m naught raise to the power 1 by 2. So, I can easily calculate the molality of the proton or H3O plus.

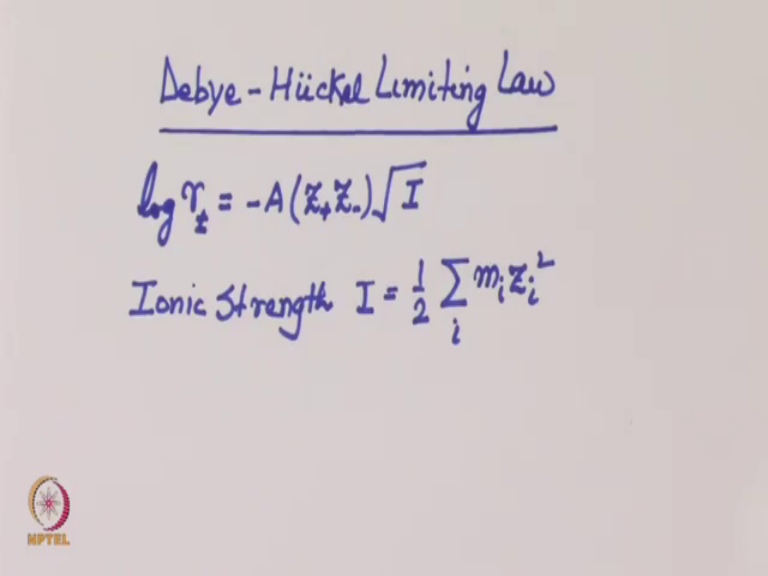
Let us now take a look at the slide. We are talking about this reaction and the acidity is due to this H3O plus. And we just derived this expression we wrote this expression in terms of molality and then since we equated this molality of ammonia equal to H3O plus we eventually came up with this expression. Now you substitute the value of Ka and the molality or molarity of ammonium chloride is given once you put that. In fact, let us consider this as molality not molarity. This molality mole per kg because we have expressed in terms of mole per kg.

So, once you substitute the answer comes out to be 9.2 into 10 raise to power minus 6 mol per kg. But this is molality. And we need activity. Activity is equal to activity coefficient in to molality divided by m 0, again m 0 is introduced here to get rid of the units.

We are given the value of activity coefficient, which is 0.6 into molality and overall activity is coming to 6 into 10 is to power minus 6 and when you substitute into the pH equation pH is minus log base 10 activity of H3O plus, the overall value comes out to be 5.2. And that is what I said in the beginning that being a very weak acid it will be lowering the pH of water from 7 pH will be less than 7 and therefore, we what we got is the pH value of 5.2.

And the point to be noted in this question is that, we were given one is to one electrolyte. And if you note down here the value of activity coefficient at 0.15 mole per kg is 0.6. 0.6 is a quite different from 1; that means, in case of electrolyte solutions or the solutions containing electrolytes, we cannot ignore the values of activity coefficient. We have to use activities. Even for a very, very dilute solution, the activity coefficient can be different than 1. And the activity coefficient can be calculated from the Debye huckel theory and if the solution is very, very dilute, one can use Debye huckel limiting law we will discuss Debye huckel limiting law bit later.

(Refer Slide Time: 27:40)



Debye - Hückel Limiting Law

$$\log \gamma_\pm = -A(z_+ z_-)\sqrt{I}$$

Ionic Strength $I = \frac{1}{2}\sum_i m_i z_i^2$

But I will just express an equation representing Debye huckel limiting law, which is log base 10 gamma plus minus is equal to minus A in to z plus z minus root I. I is ionic strength is equal to half summation i m i z i square m i. M is molality z is charged on the ion. And A is a weakly temperature dependent constant very weakly temperature dependent. And gamma plus minus is the mean ionic activity coefficient.

So, this one is Debye huckel limiting law. Limiting law means applicable at very, very dilute molality. So, while finding out the pH of a solution, especially in electrolytic systems, we must account for the activity coefficient. And that will give us the correct result. So, in today’s lecture we covered 2 important properties for biological systems, one is pH because pH is very, very important for biological systems. And second is the biological standard state Gibbs energy, and it is connection with this driving force or it is connection with the exergonicity or endergoniccity of the reaction which drives if it is exergonic it can drive the nonspontaneous processes.

So, I hope the concept of equilibrium and equilibrium constant is clear, and we will solve several numerical problems based upon the equilibrium constant and the effect of external pressure or effect of changing the temperature So that the discussion on the equilibrium constant and the concept of equilibrium constant and equilibrium becomes more clearer.

Thank you very much.