

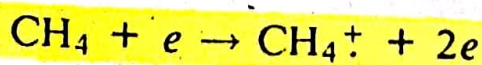
## 3.2. CHEMICAL IONISATION

Part of Section 2.1 contained a discussion of why the mass spectrometer with an electron impact ion source operates under very low pressure (about  $10^{-6}$  torr).

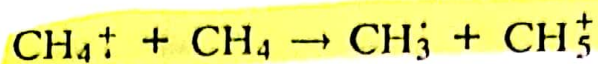
SAQ 3.2a

In that part of Section 2.1, a number of reasons were advanced for using such low pressures. Can you list them?

I want you to concentrate on just one of the points in the response to the above SAQ, which is that ions can undergo reactions with neutral molecules and this may lead to the production of new ions. This is the basis of the chemical ionisation method. Let us illustrate this by looking at the mass spectrum obtained when methane at a pressure of between 0.1 and 1.0 torr is ionised by electron impact. Initially the molecular ion is formed in the usual way.



But because of the high pressure of methane, there is a significant probability of the molecular ion colliding with another methane molecule. When this happens the most likely reaction is

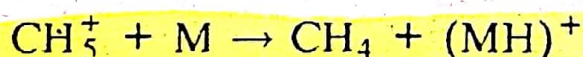


This is perhaps a somewhat surprising process as the  $\text{CH}_5^+$  ion is not one that is often encountered in solution chemistry. If you want to provoke some discussion with fellow students or chemists with whom you work, ask for opinions on the structure of  $\text{CH}_5^+$  and what orbitals might be used in its bonding.

□ We won't go into the structure of  $\text{CH}_5^+$  here, but I will ask you if you can say what general reaction type is represented by the reaction of  $\text{CH}_4^+$  with  $\text{CH}_4$ .

The answer is an acid-base reaction,  $\text{CH}_4^+$  is acting as a proton donor, an acid and  $\text{CH}_4$  is acting as a proton acceptor, a base.

Now, if a small amount of the sample to be analysed is introduced into the ion source in the vapour phase, it is species such as  $\text{CH}_5^+$  that act as the means of ionisation of the sample. This is therefore known as the *chemical ionisation* (CI) method.  $\text{CH}_5^+$  leads to ion formation of the analyte (M) usually by means of the protonation reaction shown below



The ion  $(\text{MH})^+$ , which will have an  $m/z$  value one amu greater than that of the molecular ion, is known as the *quasi-molecular ion*.

A protonation reaction of this type produces quasi-molecular ions with considerably less internal energy than is the case for molecular ions ( $\text{M}^+$ ) produced by electron impact.

SAQ 3.2b

What is the consequence of this difference in internal energies likely to be?

SAQ 3.2b

This reduced propensity for fragmentation means that the relative abundance of the quasi-molecular ion in the chemical ionisation mass spectrum is usually larger than that of the corresponding molecular ion in the electron impact (EI) mass spectrum. The comparison of EI and CI mass spectra of proline, given in Fig. 3.2a illustrate this point.

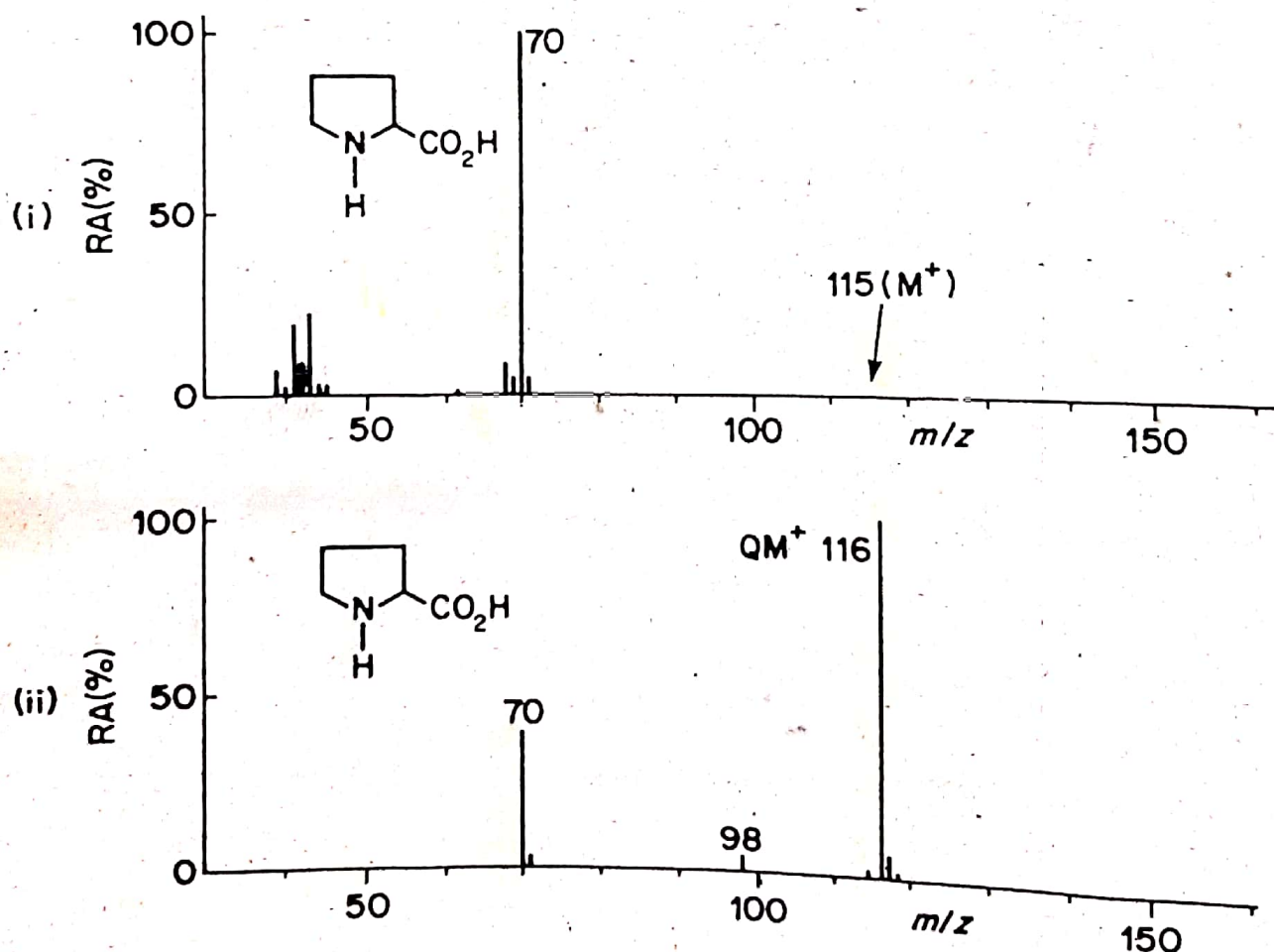


Fig. 3.2a. Mass spectrum of proline (i) by electron impact, (ii) by chemical ionisation

The CI mass spectrum should help in the determination of relative molecular masses for 'difficult' compounds.

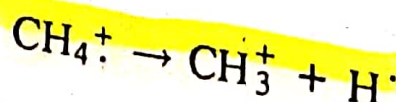
One point that may be worrying you over this method of ionisation is that if the methane, which is known as the *reactant gas*, is ionised by electron impact, what is to stop the sample, M, also forming  $M^+$  ions by an electron impact process? The answer is that the experimental conditions are designed to minimise the electron impact ionisation of M, although it does not eliminate it entirely.

II How do you think electron impact ionisation of M is minimised.

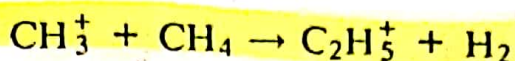
Although some sample will be ionised by electron impact, in order to ensure that a statistically insignificant proportion of sample, M, is ionised by this method compared to that ionised by chemical ionisation, we must do all we can to encourage the latter. This is achieved by using a ratio of reactant gas to sample of at least 1000 to 1, so that there is always a much higher probability of a sample molecule colliding with a  $CH_5^+$  ion than with an electron.

II The statement given earlier that CI mass spectrometry should help in establishing relative molecular masses for 'difficult' compounds has one major *proviso*. Can you think what that might be?

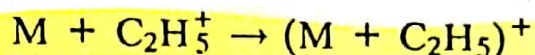
In describing the CI process, we have shown a quasi-molecular ion to be formed by protonation, thus having a mass to charge ratio one unit greater than the relative molecular mass of the compound. What we are assuming in generalising the technique is that all molecules form  $(MH)^+$  ions, so that we can infer that the highest mass ion in the CI spectrum is always one unit higher than the relative molecular mass of the sample. Although this is a very widespread occurrence, there are exceptions. These arise for two reasons. The first is that the reactant gas may undergo other ion-molecule reactions leading to other reactant ions and these may react differently with the sample. In the case of methane, the  $CH_4^+$  ion may undergo fragmentation before it collides with a  $CH_4$  molecule.



The fragment ion  $\text{CH}_3^+$  may itself undergo an ion-molecule reaction.



The formation of  $\text{C}_2\text{H}_5^+$  does occur to a minor, but significant extent and ethylation of sample molecules is also sometimes observed.



This gives  $(\text{M} + \text{C}_2\text{H}_5)^+$  ions which have a mass 29 units higher than the relative molecular mass of the molecular ion. Fig. 3.2b shows the spectrum of a molecule in which this is occurring.

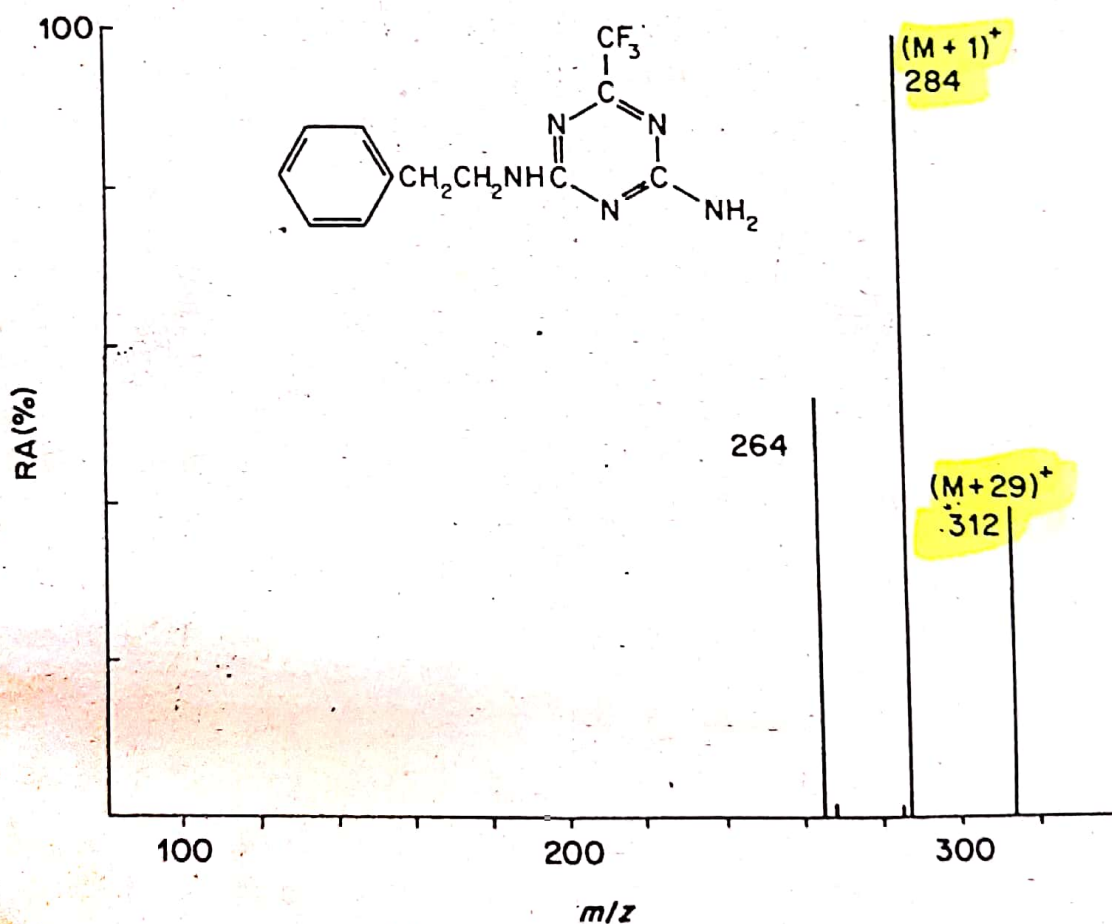
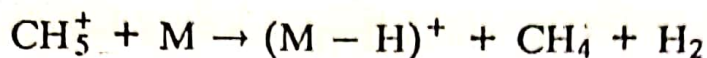


Fig. 3.2b. CI mass spectrum showing  $(\text{MH})^+$  and  $(\text{M} + \text{C}_2\text{H}_5)^+$  ions

In some cases  $\text{CH}_5^+$  does not protonate the sample. The reaction of  $\text{CH}_5^+$  with M to give  $(\text{M} + \text{H})^+$  depends on the proton affinity of M being higher than that of  $\text{CH}_4$ . If it is not, then collision between

them may still lead to a reaction, but not to simple proton transfer. The most important examples of this are the higher alkanes which have a lower proton affinity than methane and so the ion-molecule reaction proceeds as shown below.



These types of exceptions lower the value of the technique for establishing relative molecular masses, but they do not totally invalidate it, since recognising that an ion such as  $(\text{M} + 29)^+$  or  $(\text{M} - 1)^+$  may be observed is half the battle when interpreting the spectrum. The insoluble problem that makes a technique quite valueless is not knowing what to expect!

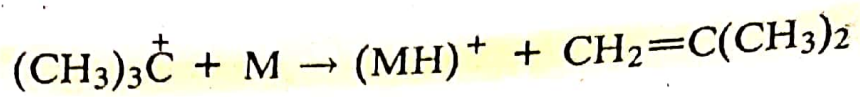
So far our discussion has been exclusively directed towards use of one reactant gas, methane. However, others are used and the most common are ammonia ( $\text{NH}_3$ ) and iso-butane ( $(\text{CH}_3)_3\text{CH}$ ).

II Without going into the full sequence of ion molecule reactions for each of these reactant gases, would you like to suggest what might be the major reactant ion each generates? In attempting this question, use your knowledge of solution chemistry in thinking about what ions are likely to be formed.

The major reactant ion from ammonia is  $\text{NH}_4^+$  and that from iso-butane is  $(\text{CH}_3)_3\text{C}^+$ . The formation of  $\text{NH}_4^+$  from  $\text{NH}_3$  directly parallels the behaviour of  $\text{CH}_4$  and, of course,  $\text{NH}_4^+$  is a well known stable cation. The behaviour of iso-butane does not directly parallel that of  $\text{CH}_4$ . If it did you might expect to form  $\text{C}_4\text{H}_{11}^+$  and I don't blame you if you wrote this down. Instead, iso-butane forms  $(\text{CH}_3)_3\text{C}^+$ , which is quite stable as it is a tertiary carbocation.

II Suggest how you might expect  $\text{NH}_4^+$  and  $(\text{CH}_3)_3\text{C}^+$  to react in ion molecule reactions.

$\text{NH}_4^+$  and  $(\text{CH}_3)_3\text{C}^+$  both protonate samples to give  $(\text{M} + \text{H})^+$  ions. You may be surprised to find  $(\text{CH}_3)_3\text{C}^+$  behaves in this way, but of course, the stable molecule, butene is formed in the process.

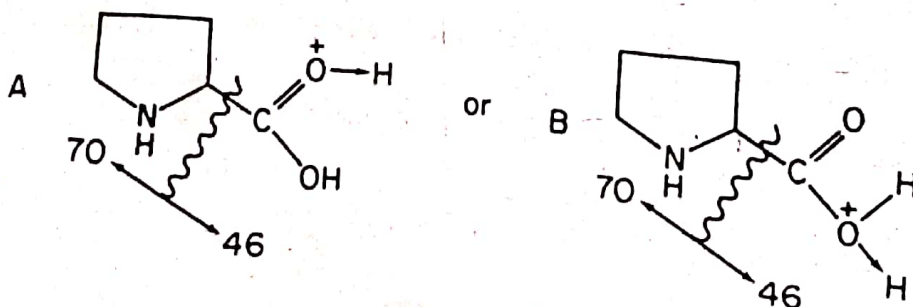


The use of these alternative reactant gases can be important in CI mass spectrometry as they may lead to different amounts of fragmentation of the same quasi-molecular ion. This is our first mention of fragmentation in CI mass spectrometry, although the spectrum of proline (Fig. 3.2a) did show fragment ions.

SAQ 3.2c

The major fragment ion in both the EI and CI spectra of proline occurs at  $m/z$  70. This represents the loss of 45 mass units from  $\text{M}^+$  in the EI spectrum and the loss of 46 mass units from  $(\text{MH})^+$  in the CI spectrum. Suggest a formula for the neutrals produced in each spectrum.

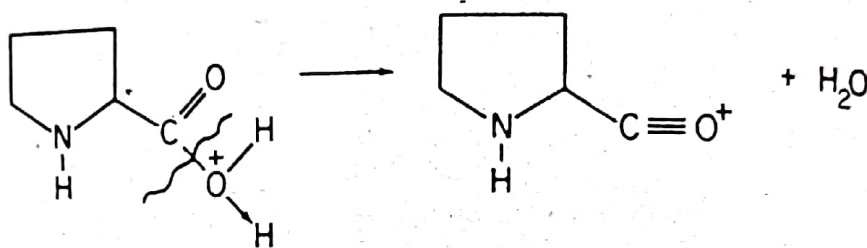
II On the basis of the loss of the 46 mass unit neutral in the CI spectrum, suggest a structure for the quasi-molecular ion.



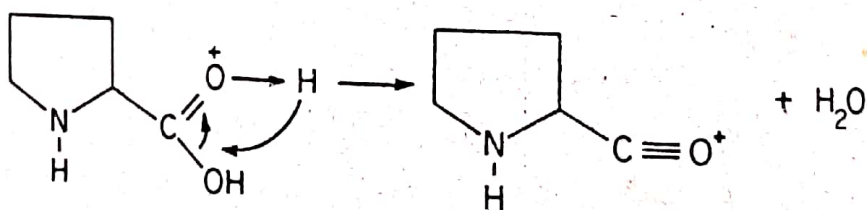
Both A and B are likely structures. In drawing these structures, I have indicated the mass of both the fragment ion and the neutral. As the formation of the quasi-molecular ion is an acid-base reaction, it is reasonable to write the product as involving electron pair donation by a lone pair on a hetero-atom. For either of the structures shown above we can readily understand the loss of a 46 mass unit neutral.

Π There is another small fragment ion in the CI spectrum at  $m/z$  98. How does this arise and does it tell us anything about the structure of the quasi-molecular ion?

$m/z$  98 corresponds to the loss of  $H_2O$  from the quasi-molecular ion. This can easily be explained in terms of structure B.



It doesn't necessarily exclude structure A as a hydrogen transfer may occur, but this is, perhaps, less likely.



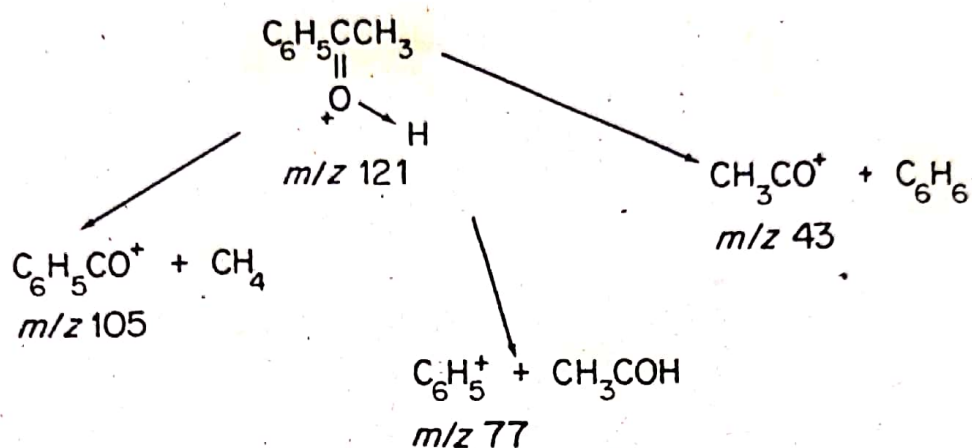
These two fragmentations, loss of  $CO_2H_2$  and  $H_2O$  do seem to suggest that protonation does not occur at the nitrogen atom, the other atom with an available lone pair of electrons.

SAQ 3.2d

Are quasi-molecular ions odd- or even-electron ions? Can you rationalise the fragmentations of the quasi-molecular ion of proline in terms of its electron configuration?



The loss of even electron neutrals is a common feature of CI mass spectrometry. As a further example, the behaviour of methylphenylketone is shown below.



This is the fragmentation pattern of methylphenylketone obtained with  $\text{CH}_4$  as reactant gas and it is interesting to compare it with that obtained using iso-butane. In this case no fragment ions, whatsoever, are observed – only the quasi-molecular ion is formed. This is the aspect referred to earlier, that the amount of fragmentation depends on the reactant gas. This arises because the amount of energy transferred to a sample molecule on protonation depends on both the proton affinity of the sample and the acidity (the willingness to release a proton) of the reactant ion.

Acidity increases in the order  $\text{NH}_4^+ < \text{C}_4\text{H}_9^+ < \text{CH}_5^+$  and thus the internal energy of quasi-molecular ion formed by these reactant ions follows the same order. As the amount of fragmentation depends on the internal energy of the ion, this explains the results given for methylphenyl ketone.

It is also worth pointing out that CI mass spectrometry can distinguish between isomers in some cases. This is illustrated by the

fact that the quasi-molecular ions of 5- $\beta$ -3-keto steroids readily lose H<sub>2</sub>O, whereas the 5- $\alpha$ -isomers hardly show this fragmentation.

In general, the amount of fragmentation of quasi-molecular ions is small or non-existent because these ions are formed with low internal energies compared to molecular ions formed by EI. The CI technique and others that also show few fragment ions are termed *soft ionisation methods*.

**SAQ 3.2e**

We have now spent a considerable time discussing CI mass spectrometry. Before we move on to the next ionisation method, list the advantages and limitations of the CI method, paying particular attention to those problems we outlined for EI at the end of Section 3.1.