Chapter 2

Principle of typical mass spectrometers

2.1 Performance of mass spectrometers

In this discussion about mass spectrometers, it is useful to introduce common criteria for comparison of the performance of each mass spectrometer. The criteria are mass resolution, mass accuracy, sensitivity and range of the mass to be measured.

2.1.1 Mass resolution

Usually, mass spectroscopy is carried out through the measurement of intensities of ions by varying such parameters as field strength or frequency. These parameters have one-to-one correspondence to the mass collected onto a focal plane detector or an ion-current meter. This ion intensity, observed as a function of the parameter, is called a mass spectrum.

The mass spectrometer is an ion-optical system, so that ions falling into the detector are distributed in a finite geometrical area depending on the source size and the focusing properties of the ion optical system. In addition to this finite area, several aberrations increase the area. If the intensity of ions is not so high, and if the interaction of each ion with other ions can be ignored, the motions of individual ions in the mass spectrometer can be regarded as independent. In this case, the above finite size and aberrations would appear as broadening in the mass spectrum due to the statistical nature of individual ion motions. Therefore, the mass spectrum is observed not as a δ-function even for only one mass m with monochromatic kinetic energy, but

as a line spectrum accompanied by broadening. In many cases, the line shape is well-approximated as a Gaussian form. This feature is schematically shown in Fig.2-1. In this dissertation, we define the mass resolution by

$$\text{Mass resolution} = \frac{m}{\Delta m} \tag{2.1.1}$$

where Δm is the full width at half maximum (FWHM) in the mass spectrum. It should be noted that the nomenclature of "resolving power" is given to the above definition in some publications.
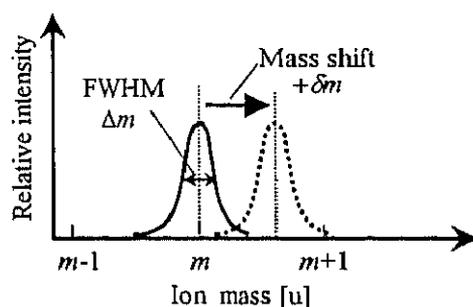

Fig.2-1 Schematic mass spectrum. Mass resolution and mass accuracy are evaluated by full width at half maximum (FWHM), Δm of mass peaks, and the shifting degree δm of mass peak positions.

2.1.2 Mass accuracy

In Fig.2-1, the solid curve is the mass spectrum observed in an actual measurement. The abscissa of the mass spectra is not the mass unit itself, but is such a physical quantity as the magnetic field [T], the flight time [s], the frequency [Hz], and so on. Any mass spectrometer, therefore, needs the calibration of the above physical quantities by measurement of mass spectra for ions for which their values of mass are known. The uncertainty in this calibration measurement is schematically shown by the dotted spectrum in Fig.2-1. The quantity δm indicated as "mass shift" is a systematic error in the standard theory of error.

2.1.3 Sensitivity

When a mass spectrometer is used for an elemental analysis, the problem becomes to how low a concentration the spectrometer will provide a reasonable counting rate of ions or an ion current for the elements to be measured. This performance is particularly important for applications to environmental sample analyses in which a detection limit down to ppb or lower levels is frequently required.

Denoting the number of ions per unit time from the ion source by I_0, the number of detected ions N can be written as

$$N = \varepsilon I_0 = \left(\frac{\Omega_G}{4\pi} \frac{\Omega_\phi}{2\pi} T\eta \right) I_0 = \frac{1}{8\pi^2} \left(\Omega_G \Omega_\phi T\eta \right) I_0 \tag{2.1.2}$$

where Ω_G stands for the geometrical solid angle subtended by the entrance of the spectrometer to the ion source, Ω_ϕ means the range of RF phase in which ions of interest are captured in stable orbits or a time focus, T is the transmission of ions through the spectrometer, and η denotes the efficiency at which the detector or the current meter produces signals above the noise level. To obtain higher sensitivity, or in other words a lower detection limit, a higher value of the factor ε is necessary.

2.1.4 Mass range

As mentioned in Subsection 2.1.1, a mass spectrum is obtained by varying the field strength or the frequency. In practice, however, the parameter is limited within a finite variable range, because of the capacity of the power supply for magnetic and electric fields or of the available frequency of an RF generator. The mass resolution and the mass accuracy are not always constant over a very wide range of the parameters. Hence, the observable mass of ions is limited in the range from the lowest to the highest values. A broad mass range becomes a key factor in

the mass spectroscopy of high molecular weight ions extracted from such samples as organic or biological materials.

2.2 Mass spectrometers based on static magnetic and electric sector fields

A mass spectrometer is comprised of an ion source, a mass analyzer and an ion detector or an ion current meter. The ion source produces ions of interest for analysis by low-pressure gas discharge or several other methods. The ions extracted from the ion source are then accelerated through a static electric field up to a definite kinetic energy. In many cases, a narrow ion beam having a limited transverse momentum with respect to the direction of flight is formed with an appropriate slit system before it is injected into the mass analyzer.

For an ion with the charge q and the mass m, the forces given by an electric field E and a magnetic field B are as follows;

$$F_e = qE \qquad \text{and} \qquad F_m = \frac{q}{m}(p \times B) \qquad (2.2.1)$$

Since the change in ion momentum is produced by the corresponding impact $F\Delta t$, only the magnetic force F_m brings about a change in the ion momentum which depends on the mass m. Hence a magnetic field is indispensable to the measurement of q/m.

The principle of the mass spectrometer using a uniform magnetic field with a sector type field boundary is schematically shown in Fig.2-2(a). It is well known that an ion injected into a uniform magnetic field at a direction perpendicular to the field moves along a circular orbit. The uniform magnetic field, therefore, deflects the flight direction of the ion. After the transit through the uniform field, the ion travels along a straight line again. The angle of deflection is determined by two straight lines extended from the field boundaries.
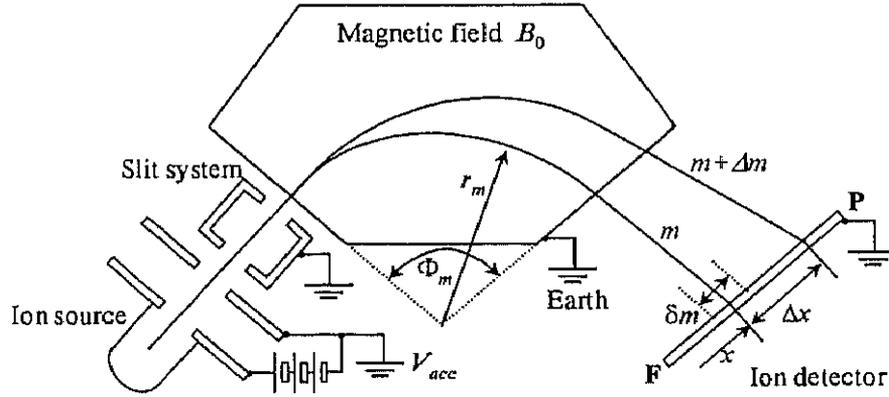
Fig.2-2(a) A schematic drawing of a mass spectrometer using a uniform
sector field. The marks of the electrical earth indicate that the electrical
potentials at those points are maintained at the ground potential. The space
where ions travel from the ion source to the F-P plane must be maintained at
a pressure lower than ~ 1 × 10⁻⁵ Pa in order to reduce the transmission loss of
ions due to collisions with residual gas atoms.

Denoting the field strength by B_0, the radius of curvature r_m is given by

$$r_m = \sqrt{2 \frac{m \, V_{acc}}{q \, B_0^2}}$$

(2.2.2)

where the kinetic energy of the ion entering into the uniform field is expressed in units of eV

with the accelerating voltage V_{acc}. In the arrangement of Fig.2-2(a), the ion detector is placed at a

fixed position in the space after the ion deflection. Under the condition that B_0 and V_{acc} are fixed,

another ion with the mass $m+\Delta m$ ($\Delta m > 0$) travels along a circular orbit of larger radius of

curvature than r_m in the uniform magnetic field. After the transit of the field, the ion with the

mass of $m+\Delta m$ arrives at a position displaced by Δx on the plane FP. Conventional ion sources

such as a radiofrequency source or a low-voltage arc ion source mainly produce singly charged

ions. The charge q can mostly be assumed to be an elementary charge of $q=e_0$. Thus, the ion of

mass m can be discriminated from the ion with the mass of $m+\Delta m$, if a narrow slit is placed in

front of the ion detector. The mass spectrum is obtained from the measurement of the number of

13

ions deflected into the ion detector per unit time as a function of B_0^2. For the ion detector, pulse counters like secondary electron multipliers or a high sensitivity current meter can be used.

The mass resolution of this type spectrometer is directly related to the displacement Δx shown in Fig.2-1(a). This depends upon the parameters of the deflection angle Φ_m, the radius r_m, the distances between the source to the entrance of the magnetic field and between the exit of the field to the ion detector. The geometrical size of the source and the ion detector bring about deterioration of the mass resolution also. Detailed descriptions of $m/\Delta m$ have been given in ref.[11].

To obtain higher mass resolution, we have to use a large radius of curvature, long distances for both source-to-field and field-to-detector, and narrow slits for the beam formation and for the ion detector. All of these, however, result in low sensitivity. Furthermore, the kinetic energy of ions is not constant rigorously, but is a superposition of an average value and fluctuation due to the voltage ripple in V_{acc}. The energy spread produced in the ion source must be included in the fluctuation of V_{acc}.

From detailed investigations on the ion orbits in a system consisting of electric and magnetic fields, it has proved that the ion orbits are analogous to light paths in an optical lens system. Outstanding results of the investigations were findings of "directional focusing" and "velocity focusing". The directional focusing is very similar to the focusing of light through a convex lens. A parallel light beam converges to a point located at the distance of the focal length behind the convex lens. Similarly, a parallel ion beam entering a sector type electric or magnetic field converges to a focal point after the transit of the field. If we use this property, ions emerging from a source point with a certain divergence of angles can be collected again at an image position. The velocity focusing is based on the fact that the electric field introduces energy dispersion into an ion instead of momentum dispersion. This is easily understood from the

motion of an ion in the electric field generated between coaxial cylindrical electrodes. Since the electric field has its radial component only, the ion moves along a circular orbit. The radius of curvature r_e is expressed by

$$r_e = \frac{2K}{qE_0} \qquad (2.2.3)$$

with the ion kinetic energy K and the strength of the electric field E_0.

We can construct a mass spectrometer having the directional and velocity focusing properties (double focusing) by means of a combination of electric and magnetic sector fields. Many variations exist. Fig.2-2(b) shows an example of the double focusing mass spectrometer[12] reported by Mattauch[13] and Herzog. Ions from the ion source are focussed once onto a narrow slit S located at the object focal distance of l_s by a certain converging lens. The deflection angle of the electric field is chosen to be $\Phi_e = \pi/(4\sqrt{2})$. The narrow slit S can be regarded as the source, and ions emerging from S have various values of velocity and q/m. The diverging beam from S becomes a parallel beam at the exit of the electric field. This parallel beam converges to a point at the boundary of the magnetic field. The solid lines indicate the orbits with a definite energy K (velocity v) and the chain line denotes the average one among the orbits of the ions with the energy K. The broken line represents an orbit of a different ion with larger energy K' (velocity v') than K, but with the same value of q/m. The broken line is displaced from the solid line due to the energy dispersion in the electric deflection. However, the two ions finally converge on the same point. The double focusing achieved in this way is very helpful for increased sensitivity.
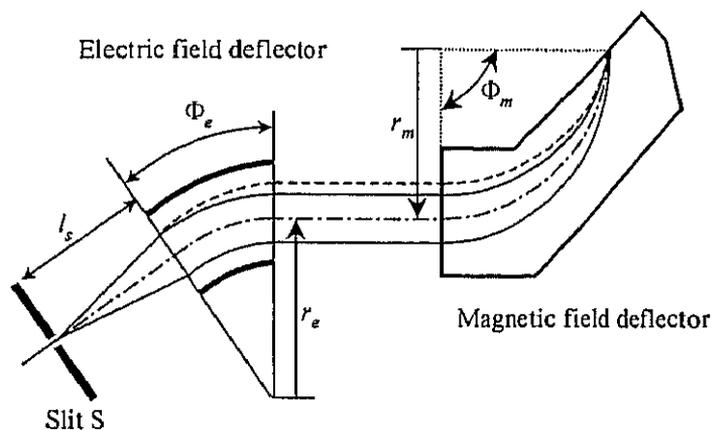
Fig.2-2(b) The double focusing mass spectrometer reported by
Mattauch[13] and Herzog.

The most powerful performance factor of the sector type mass spectrometer is its very high

mass resolution. Typical mass resolutions range from 10^4 to 10^5. The mass range covers up to 10^5

[u]. Mass accuracy of the order of 10^{-2} % is obtainable. Recently, the double focusing type mass

spectrometers have been used for measurements of some polymer molecule masses. Wada[14]

reported that one protein of 11729.2[u], that is β_2-microglobulin, was measured with mass

resolution of about 30,000 and mass accuracy of 0.05%. On the other hand, the system usually

has a very large geometrical size and it is very heavy because of the large-volume electromagnet.

The investment and running costs are much higher than those of RF-QMF or ITMS systems.

2.3 Time-of-flight mass spectrometers

Time-of-flight mass spectrometers (TOF-MS) utilize differences in the transit time when ions

with a definite kinetic energy drift across a field-free space with a definite length. The principle

can easily be understood from Fig.2-3(a). The ions extracted from the ion source are accelerated

by a static voltage of V_{acc}, and then drift through the field-free space with the length L.
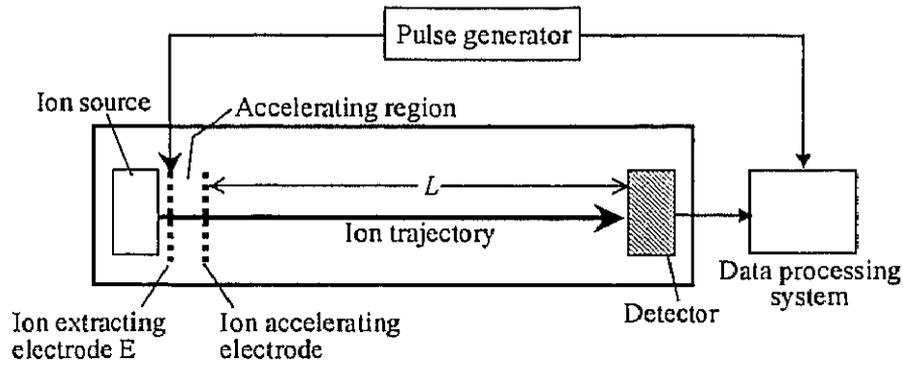
Fig.2-3(a) Schematic diagram of linear mode type of TOF-MS.

For measurement of differences in transit time among ion species, it is necessary to make a pulsed beam to define the start time. Methods to make pulsed beams differ according to the type of ion source. One example is shown in Fig.2-3(a). A pulsed beam is made by applying a pulse voltage to ion extracting electrode E. The duration of the pulse voltage application is shorter than the flight time. We can define the origin of the transit time to be the timing when the ions are extracted from the ion source to the accelerating region.

After the drift through the field-free space, ions incident on the detector placed at the opposite side of the ion source produce signals of the arrival time. Taking the start time as t_{start}=0, and writing the arrival time and the length of the field-free space as t_a and L, respectively, the following relation is obvious;

$$t_f = t_a - t_{start} = L\sqrt{\frac{m}{2qV_{acc}}} \tag{2.3.1}$$

where t_f is defined as the flight time hereafter. It should be noted that all of the ion paths are assumed to be parallel in the above discussion. This is a reasonable assumption in most cases. The time t_f can directly be obtained as a digital quantity using a time-to-digital converter.

The mass resolution of TOF-MS depends on the uncertainties of the measurement of the flight time t_f, the variance of the length L and the spread of the kinetic energy. The uncertainty of t_f is small enough if measurements are performed with recent techniques in fast electronics and such detectors as secondary electron multipliers. The variance of L is mainly due to the difference of flight paths caused by different initial positions and directions of ions at the entrance of the field-free drift space. The spread of the kinetic energy is introduced in the ion source and the accelerating region.

To reduce the effect of the fluctuation due to the space and energy spread on the flight time t_f, a reflectron was developed[15]. Fig. 2-3(b) shows the basic concept of the reflectron which consists of an ion source, an accelerating and pulsing system, an ion reflector, and a detector. When the ions emerge from the accelerating region at angle α from the ion source, they are assumed to have a velocity spread from $v_0 - \Delta v_0$ to v_0 even when they have the same value of m/q. The spread of the flight time in the field-free drift space is expressed by

$$\Delta t_{f1} = \frac{1}{v_0 - \Delta v_0} \cdot \frac{L}{\cos\alpha} - \frac{1}{v_0} \cdot \frac{L}{\cos\alpha} = \frac{\Delta v_0}{v_0(v_0 - \Delta v_0)\cos\alpha} L .$$ (2.3.2)

In the reflecting region the electric field E_{ref} is formed in the opposite direction of the ion flight. Ions entering into the reflector with higher kinetic energies invade deeper into the reflection field. Therefore, it takes a longer time for those ions to return to the entrance of the reflecting region. The spread of the time needed for ions to return to the boundary of the reflection field is given by

$$\Delta t_{f2} = \frac{2m(v_0 - \Delta v_0)\cos\alpha}{qE_{ref}} - \frac{2mv_0\cos\alpha}{qE_{ref}} = -\frac{2m\Delta v_0\cos\alpha}{qE_{ref}} .$$ (2.3.3)

Finally, the time spread for ions to transit from the boundary of the reflecting region to the detector is expressed in the following form:

$$\Delta t_{f3} = \frac{1}{v_0 - \Delta v_0} \cdot \frac{L'}{\cos \alpha} - \frac{1}{v_0} \cdot \frac{L'}{\cos \alpha} = \frac{\Delta v_0}{v_0(v_0 - \Delta v_0)\cos \alpha} L' \qquad (2.3.4)$$

where L ' is the distance between the boundary of the reflecting region and the detector.

Therefore, the total time spread is obtained as follows:

$$\Delta t_f = \Delta t_{f1} + \Delta t_{f2} + \Delta t_{f3} \approx \frac{qE_{ref}(L + L') - 2mv_0^2 \cos \alpha^2}{qE_{ref}v_0(v_0 - \Delta v_0)\cos \alpha} \Delta v_0 \; . \qquad (2.3.5)$$

Thus, by adjusting the reflection field E_{ref} so as to make the value of the numerator of eq.(2.3.5) close to 0, theoretically, the energy spread can be eliminated.
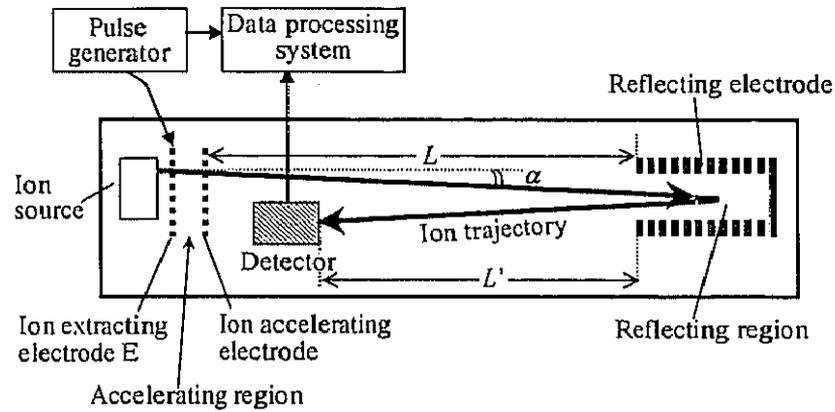
Fig.2-3(b) Schematic diagram of reflectron.

The advent of the reflectron has greatly improved mass resolution. For example, measurement of 200 fmol of a polymer molecule, *globin*, of 15868[u] with mass resolution of about 2,000 and mass accuracy of 0.1% was reported[16]. Although its mass resolution is not high in comparison with other type of mass spectrometers, TOF-MS has a remarkable characteristic that there is no theoretical upper limit for the mass of ions which can be analyzed. A TOF-MS system can be constructed in a moderate size. The costs for investment and operation are also not so high. These features of TOF-MS make it very attractive and promising for mass spectroscopy of materials involving proteins, polymers, and other large molecules.

19

2.4 Ion cyclotron resonance mass spectrometers

It is well known that the motion of a charged particle in a uniform magnetic field is a circular motion in a plane perpendicular to the magnetic filed. The radius r_m of curvature is given by eq. (2.2.2). If we note the relations of $\sqrt{2mqV_{acc}} = mv$ and $v = r_m\omega_c$, we obtain the following relation from eq. (2.2.2):

$$f_c = \frac{\omega_c}{2\pi} = \frac{qB_0}{2\pi m}$$

(2.4.1)

where v stands for the ion velocity along the circumference and ω_c means the angular velocity of circular motion. The frequency f_c is known as the cyclotron frequency and it is independent of ion velocities. This fact, which was the starting point for development of the cyclotron accelerator, can be applied to mass spectroscopy.
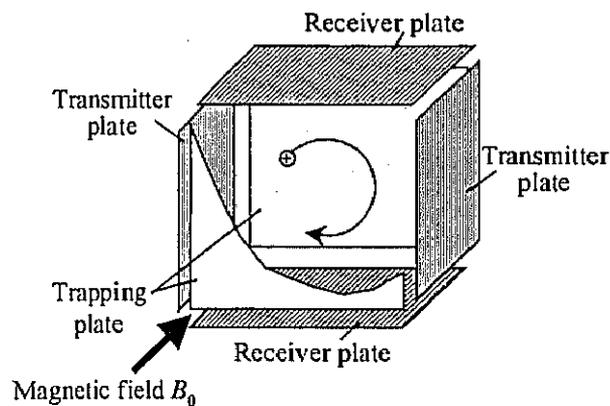

Fig.2-4 Schematic diagram of the cell of ICR-MS.

Fig.2-4 shows the concept of an ion cyclotron resonance mass spectrometer (ICR-MS). It is comprised of ion trapping plates, transmitter plates and receiver plates. The space surrounded by the set of parallel plates is called the ICR cell. We apply a certain value of voltage to the ion trapping plates, so that an electric field is generated along the magnetic field. The electric field confines ions in the ICR cell. All ions of the same values of q/m have an identical cyclotron

frequency of f_c^{ion}. They are moving independently in a random phase at roughly thermal energy. If we apply an external excitation pulse at a frequency f_{ext} to the transmitter plates, "resonant ions", namely ions moving with $f_c^{ion} = f_{ext}$, are accelerated according to the principle of the cyclotron. The radius r_m of these ions increases. The resonant ions which approach the surfaces of the receiver plates induce an image current on the plates. The magnitude of the image current should be proportional to the number of resonant ions. Thus, we can measure q/m from the frequency of the external excitation pulse at $f_{ext} = f_c^{ion}$ and the population of such ions from the image current.

If several different ion species are present in the ICR cell, the frequency f_{ext} can be changed step by step. The more efficient method, however, is that we apply an external excitation pulse containing a wide range of frequencies to induce resonance for all q/m of different ions species. The former method is a rapid frequency sweep. In the latter method, we apply the external excitation pulse with a tailored waveform. In this case, the image current contains all frequency components corresponding to q/m. Although this image current is a complicated function of time involving various components of frequencies and corresponding amplitudes, it can be converted to a spectrum in the frequency domain with the aid of a Fourier transform method. The spectrum converted in this way is the mass spectrum. This method is Fourier transform ICR-MS (FTICR-MS).

At present, elaborately designed FTICR-MS provides the highest mass resolution of the order of $10^5 - 10^6$. For example, a high-resolution mass spectrum of 23+ charged carboxypeptidase (34,000[u]) was obtained with mass resolution of 150,000 with mass accuracy below 0.01%[17]. High sensitivity is also an attractive feature of FTICR-MS. For example, the mass spectrum of 50 fmol of a peptide antagonist was observed[18].

Most modern FTICR-MS systems use superconducting magnets. They require an ultra high

vacuum system to get low pressure in the ICR cell. Consequently, the systems are relatively large

and expensive.

2.5 Radiofrequency quadrupole mass spectrometers

The present dissertation is aimed at improvement of the performance of RF-QMF and ITMS.

More detailed discussions appear in later chapters. Therefore, only very brief descriptions of the

principle of RF-QMS and ITMS are given here for comparison of concepts of individual mass

spectrometers.

Radiofrequency quadrupole mass spectrometers (RF-QMS) utilize the fact that m/q depends

on the frequency of ion oscillation in a quadrupole RF electric field. This type of mass

spectrometer was first reported by Paul and Steinwedel[19,20] in 1953. According to the number

of dimensions of the quadrupole field, RF-QMS is classified into quadrupole mass filter (RF-

QMF) and ion trap mass spectrometer (ITMS) types[21,22].

RF voltages

$+\Phi_0$ $-\Phi_0$ $\Phi_0 = U - V_{RF} \cos \Omega t$

Ion source

Focusing lenses

$2r_0$

Ion trajectory

Shield case
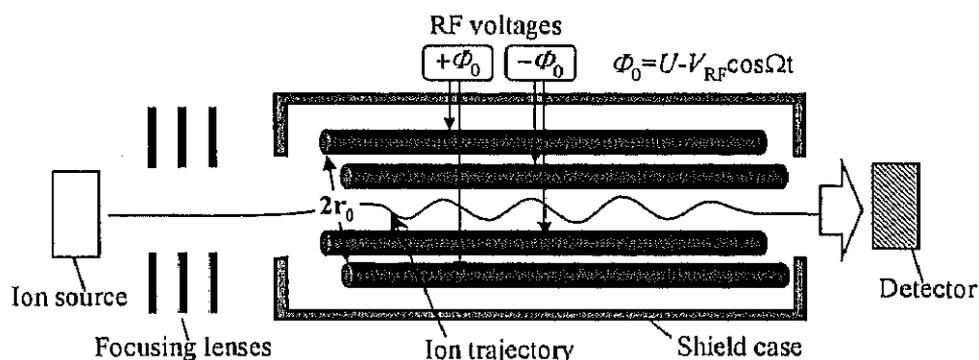
Detector

Fig.2-5(a) Schematic diagram of RF-QMF.

Fig. 2-5(a) shows a schematic drawing of the RF-QMF. It is comprised of an ion source with a focusing system, four rod electrodes working as a filter, and an ion detector. In a plane perpendicular to the four rods, a two-dimensional RF electric quadrupole field is generated. Among ions injected into this field, only ions having a selected m/q pass through the four rod electrodes. Further discussions are presented in Chapter 3.
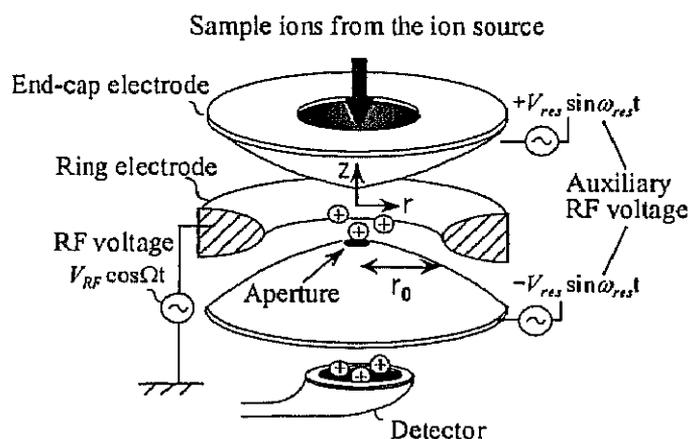

Fig.2-5(b) Schematic diagram of ITMS.

The principle of ITMS is displayed in Fig.2-5(b). The two end-cap electrodes and a ring electrode generate a three-dimensional RF quadrupole field in the space surrounded by these electrodes. Ions for which m/q ratios are to be measured are injected from one end-cap electrode and trapped in a volume near the center. We apply balanced (out-of-phase) resonance AC voltages ($\pm V_{res} \sin \omega_{res} t$) to each end-cap electrode together with an RF voltage($V_{RF} \cos \Omega t$) supplied to the ring electrode. The ions having a specific m/q ratio fulfill the resonance condition determined by m/q and the amplitudes and frequencies of applied voltages. These resonant ions oscillate with increasing amplitudes and eventually exit from ITMS to the ion detector.