Magnetron Type Mass Spectrometer

SHIGERU NAKAGAWA*

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A small and simple mass spectrometer was constructed which utilized the magnetron characteristics of cutting off the ion currents successively according to their masses by scanning the magnetic field, and the isotopic contents of lithium were analyzed using the center filament as a surface ionization source. By superimposing a small a.c. voltage on a constant accelerating voltage, stepped ion currents collected on the outer cylindrical electrode were modified and a conventional mass spectrum was recorded.

1. Introduction

Utilizing the magnetron characteristics of cutting off the current in a cylindrical diode with an axially applied magnetic field, Smith, Parkins and Forrester¹⁾ had constructed a radial magnetic separator, and a similar device had been independently proposed by Ewald²⁾. For these isotope separators in which the intense ion currents are required the constructions are rather complicated. For mass spectrometer use, however, the requirements are comparatively simple. The present author has intended to make a small and simple mass spectrometer replacing the cathode in the non-split anode magnetron by a surface ionization source and obtained a good result which predicts the present apparatus to be applicable to practical uses.

2. Principle and Apparatus

A schematic view of the apparatus is shown in Fig. 1. A surface ionization source lies on the

Fig. 1. Schematic view of the apparatus.

Fig. 2. Ion trajectories. ($M_1 < M_2 < M_3$)

axis of the cylindrical ion collector, and between both electrodes a d.c. voltage by which ions are to be accelerated to the collector is applied in the presence of a magnetic field parallel to the axis.

When the applied magnetic field is sufficiently weak in its intensity under a constant accelerating voltage, all ions from the source will reach the collector. However, as the magnetic field intensity is increased, the ion currents would be cut off successively corresponding to their masses as shown in Fig. 2, and the stepped currents flow onto the collector (Fig. 3). In the case of the critical cut-off, if the space charge effect and initial velocities of ions are neglected, the relation between the mass to charge ratio m/e of an ion and the magnetic field intensity is given by

* Rikagaku Kenkyusho (The Institute of Physical and Chemical Research)
31, Kamifujimae-cho, Komagome, Bunkyo-ku, Tokyo.

$$B_c = \sqrt{8 \frac{m}{e} V} / R \left(1 - \frac{r^2}{R^2}\right), \quad (1)$$

where V is the potential difference between the ion source and the collector, r and R are their radii, all in m.k.s. units. Accordingly, when the dimensions of the apparatus are given, the mass to charge ratio of an ion is represented by the magnitude of the potential difference between both electrodes and the magnetic field at the critical cut-off, and the amounts of ions present are given by the height of the steps in current. From Eq. (1) it is clear that the step-characteristics of ion currents at critical cut-off will be obtained either by varying the magnetic field or the electric potential keeping another variable constant respectively. In practice, however, there exist some problems* in general in the case of potential scanning.

Fig. 3. Ideal step-current characteristic.

Fig. 4. Apparatus.

Fig. 5. Proposed method #1 displaying the mass spectrum from step-current characteristics.

An apparatus used for the present experiments is shown in Fig. 4. The ion collector is a tube of non-magnetic stainless steel (SUS 32), 20.2 mm in its inner diameter and 30 mm in length. As the smoothness of the inner surface of the collector affects the resolution of apparatus, it was carefully finished. The ion source is of a surface ionization type, the sample being coated on the filament. The magnetic field was applied with an electro-magnet; the pole-pieces were 300 mm in diameter and the gap was 60 mm. When the apparatus is operated with so high accelerating voltage as the initial velocities of ions can be neglected, Eq. (1) is to be used approximately for analyses. In the present experimental apparatus, since $R=10.1$ mm and $r=0.08$ mm, then $(r/R) \ll 1$ in Eq. (1) and the critical magnetic field can be written in the abbreviated form;

$$B_c(\text{gausses}) = 286 \sqrt{M \text{ (a.m.u.)} \cdot V \text{ (volts)}}, \quad (2)$$

in terms of practical units and atomic mass unit for singly charged ions.

A Method of Mass Spectrum Display

As mentioned above, from the stepped current obtained by scanning the magnetic field under a constant accelerating voltage the masses and the relative contents of ions can be read out, but it would be more convenient to display the mass spectrum in the conventional form. In order to obtain such a spectrum, a modulation method has been applied.

* See 4.2-(2)

Fig. 6 shows the a.c. amplifier and the demodulator used to obtain the mass spectrum. The synchronous demodulation contributes to improve the S/N ratio. The overall gain of the circuit is about 100 db for 10 kc, the frequency to modulate the ion currents.

It is found that the intensity ratio ${}^7\text{Li}^+/\text{}^6\text{Li}^+$ measured from Fig. 9 is rather large compared with that shown in Fig. 7. Moreover, it was always observed that the ratio increased slowly with time, which was probably due to the isotopic effect of the elements.

Fig. 7. Step-current characteristic obtained by magnetic scanning.

Fig. 8. Step-current characteristic obtained by electric scanning.

Fig. 9. Mass spectrum.

4. Discussion

4.1 On the Deviation of Results from Ideal Characteristics

As observed in Figs. 7 and 8 the step-current characteristics obtained in the present experiments were considerably distorted. The causes for these soft-slope characteristics may be explained as follows:

- Deviation of the electric field from a purely radial field,
- Non-uniformity of the magnetic field,
- Non-orthogonality of the electric and the magnetic field,
- Non-uniformity of the initial velocities of ions,
- Influence of the space charge.

In these causes, (a), (b) and (c) would be resolved to fairly good extent. If the accelerating voltage is kept high enough, the influence of (d) also may be minimized. Under the condition of $(r/R)^2 \ll 1$ in Eq. (1), the expression of the reciprocal resolution is given by

$$\frac{\Delta M}{M} = 2 \left(\frac{\Delta R}{R} + \frac{\Delta B}{B} \right) - \frac{\Delta V}{V}, \quad (3)$$

from which the influences of the cause (a) due to the geometrical asymmetry and of the cause (b) together with the influence of the instability of acceleration voltage on the resolution of the apparatus can easily be estimated. On the contrary, however, it would be difficult to estimate the influence of the space charge on the resolution; in practice, this effect may be negligible where the ion current is sufficiently small.

4.2 On the Spectrum Display by the Modulation Method Proposed

(1) *The effects of the amplitude of superimposed a.c. voltage on the resolution and the peak height ratios.* For the ideal step characteristics as shown in Fig. 3 the higher resolution will be obtained by reducing smaller the amplitude of a.c. voltage superposed on the d.c. accelerating potential without losing the proportionality of the output-amplitudes to the heights of the step currents. For the distorted current characteristics, however, the amplitude of a.c. voltage superposed should be kept larger than a certain values under which the proportionality of the amplifier outputs to the heights of the steps would be lost. To obtain the accurate abundance ratios of the ions present, the amplitude of a.c. voltage should be set at the minimum value keeping the flat-top characteristics of the spectrum recorded.

(2) *Another method of spectrum display.* As shown in Fig. 10, the mass spectrum would be obtained also by superimposing a small a.c. voltage of higher frequency on the slowly scanned acceleration voltage under a constant magnetic field. In this method, however, the abundance ratios of ions obtained may involve some errors due to the leakage current between electrodes, initial velocities of ions, and space charge, those would vary depending upon the accelerating voltage.

Fig. 10. Proposed method #2 displaying the mass spectrum from step-current characteristics.

5. Conclusion

A small and simple mass spectrometer of magnetron type was constructed and the performances were checked analysing lithium sample coated on the center filament. The apparatus would be improved in its characteristics as discussed in 4.1, and it would be useful for some purposes because of its simplicity. When the center filament used as a surface ionization source was replaced by an electron beam, the apparatus would be expected to be used as a leak detector or an ionization gauge to measure the partial pressure of a vacuum system.

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References

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