Mass Spectrometers with Magnetic Focusing Prisms

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***Abstract*—The technique and the results of theoretical and experimental investigations of ion-optical properties and characteristics of mass spectrometers with magnetic focusing prisms have been described. The prospects of such devices for the ion beam analysis in mass spectrometry were shown.**

***Keywords*—Mass spectrometer; prism; Ion beam; resolution; magnetic field; dispersion.**

I. Introduction

The task of further development of mass spectrometers with magnetic fields may be solved successfully owing to the search and developing of novel, more efficient methods of ion beam focusing and separation. In this regard, one may find promising the application of axially symmetric prism inhomogeneous magnetic fields which may be tentatively divided in two groups: devices with magnetic ion focusing by the direction [1-3] and the ones with electric focusing [4]. The ion focusing by the direction in the mass analyzer with the heterogeneity factor n = 1 may be realized with the help of curved limits of the magnetic field or using the lenses in the case of straight limits of analyzer's magnetic field. Application of electric ion focusing by the direction provides the mass analyzer with several advantages, namely: it's not necessary to use complex curved limits of polar tips of mass analyzer's magnet and high precision assembly of ion-optical system's elements; large dispersion is achieved at a relatively small magnet size; the influence of spatial charge of ion beam and scattering magnetic fields on the analytical parameters of the instrument is decreased.

II. Physical and Technical Peculiarities and Application

The instruments with inhomogeneous magnetic field ($0 \le n \le 1$) were produced in the former USSR and abroad [5, 6]. They provided several interesting opportunities for the materials analysis, however, in present their use is limited because of no possibility to reach high resolution at low peak intensity. Nevertheless, the developers of mass spectrometers continue to search for new ways to use the magnetic prism mass analyzers with inhomogeneous field. This is due to a desire to apply the useful properties of magnetic field with the heterogeneity factor $n = 1$ (the field of r^{-1} type). As compared to the homogeneous field and inhomogeneous field whose heterogeneity factor $n < 1$, the r^{-1} field has a number of useful features, namely:

Dispersion of r^{-1} magnetic field, according to [3], grows proportionally to the square of the angle of ions turn in the magnetic field, and may be large enough at a relatively small size of the mass analyzer.

The r^{-1} field focuses ions more efficiently in the axial plane, which enlarges the sensitivity of the mass spectrometer.

The r^{-1} field does not focus ions in the radial plane, which opens new prospects in the optimization of mass spectrometer parameters.

Magnetic field r^{-1} may be relatively easy realized since it may be formed in space between the magnet poles with the surface in the form of bicones with the top at the centre of the system.

Mass analyzers with the focusing magnetic prisms were firstly applied in beta mass spectrometry [1]. Afterwards, N.A. Shekhovtsov used them in mass spectrometry [2]. He built the instrument with two independent mass analyzers which measured simultaneously two ion currents from any part of the mass spectrum [3]. Later, A.F. Malov, V.A. Suzdalev, and E.P. Fedoseev have investigated the ion-optical properties of the r^{-1} field and shown its advantages over homogeneous and known at present inhomogeneous magnetic fields [7-9]. The results of these investigations were the basis for the development of large separator of charged particles with high ion-optical parameters [10]. In the mass analyzer with the r^{-1} magnetic field the round limits play a role of the focusing magnetic lenses, they provide the second order focusing by the direction.

In the monograph [11] it is considered the ion-optical properties of the mass analyzers with the wedge-shaped inhomogeneous magnetic field, and it is determined the geometric parameters of the field at which the stigmatic focusing of the ion beam is ensured as well as the second order angular aberrations are removed. The structure and the characteristics of the devices with the wedge-shaped inhomogeneous magnetic fields are described in [12-14]. It should be noted that in the prism mass spectrometers with inhomogeneous magnetic field, as a rule, sector fields are used, because the ion source and the ion collector should be maintained beyond the main magnet. As compared to the instruments in which two-dimensional prism magnetic fields are used, the mass spectrometers with the r^{-1} field have higher dispersion values at the same size of the ion-optical system. The experience in the development and application of prism mass spectrometers with the r^{-1} magnetic field have shown that the necessary parameters of such instruments may be obtained only at high precision making of the limits form of prism magnetic field. For instance, the deviation of the divergence angle value from the calculated one by 1 % decreases the resolution of the instrument by 30 %. The profile of the prism limits is necessary to select experimentally.

H. Matsuda have suggested and practically implemented another method of ion focusing by the direction in the ion-optical system with the r^{-1} magnetic field, which is based on the use of additional homogeneous magnetic field. This idea was applied during the development of the mass spectrograph with very high resolution. Constructively an ion-optical system of this device was made of three consecutively placed analyzers: electrical and two magnetic, one of which has the r^{-1} field, and another one – homogeneous field which focuses ions by the direction and velocity. Geometric and physical parameters of all the three analyzers were selected in a way to fulfill the condition of ion focusing by the direction and velocity which has the form:

$$\frac{2}{K_e}\sin K_e\Phi_e = \Phi_{m1} + \sin\Phi_{m2}, \qquad (1)$$

where K_e – the constant which characterizes the electric field; Φ_e – the angle of ion deflection in the electric field; Φ_{m1} – the angle of ion deflection in the inhomogeneous magnetic field; Φ_{m2} – the angle of ion deflection in the homogeneous magnetic field.

Upon the following geometric parameters of the analyzer: $r_e = 300$ mm; $\Phi_e = 118.7°$; $r_{m1} = 220$ mm; $\Phi_{m1} = 198.1°$; $r_{m2} = 1200$ mm; $\Phi_{m2} = 30°$ the dispersion of the mass spectrometer is 14 mm by 1 % of the mass, which allowed to reach the resolution of 500000. The second order geometric aberrations were corrected.

The investigation of ion-optical properties of inhomogeneous magnetic fields with axial symmetry shows that the mass analyzers built on their basis are useful for separation and focusing of charged particles homogeneous by mass and inhomogeneous by velocity or homogeneous by velocity and inhomogeneous by mass. If the beam parameters are such that the particles in it are different by mass and velocity then the advantages of inhomogeneous field over the homogeneous one will be notable during the separation of wide ion beams when the contribution of aberrations in image widening is less than the starting beam width at the ion source output.

Certainly, the attractive feature of magnetic prisms with the r^{-1} field is large dispersion. As it was shown in [15], for the symmetric construction of the mass analyzer with inhomogeneous sector magnetic field the dispersion by masses is determined using the expression:

$$D_m = \frac{r_m}{2}\left(\frac{1-\cos\sqrt{1-n}\phi_m}{1-n} + l''_m\frac{\sin\sqrt{1-n}\phi_m}{\sqrt{1-n}}\right) \qquad (2)$$

If the heterogeneity factor $n = 1$ then taking into account that

$$\lim_{n\to1}\frac{1-\cos\sqrt{1-n}\phi_m}{1-n} = \frac{\phi_m^2}{2}; \quad \lim_{n\to1}\frac{\sin\sqrt{1-n}\phi_m}{\sqrt{1-n}} = \phi_m,$$

one obtains $D_m = \frac{r_m\phi_m^2}{4} + \frac{l''_m\phi_m}{2}$. (3)

The first summand in the relation (3) characterizes the radial dispersion, the second one – angular dispersion. As one can see, the dispersion of the r^{-1} magnetic prism by masses is proportional to the square of the angle of ion deflection and may be large enough when $\varphi_m > 180°$. Upon this, the dispersion enlargement owing to the selection of large angles of ion deflection in the prism or the mass range widening *via* the enlargement of the radius of the central path of the ions will not lead to the enlargement of the "optical shoulders" and size of the instrument because the radial ion focusing in the prism is ensured independently on these parameters. High technical parameters of the H. Matsuda's instrument, which represents the unique installation, were achieved mainly due to the complexity of ion-optical system design and its size enlargement (the length of the ions path from the source to the collector is 7 m, the instrument mass is several tons).

III. CONCLUSION

The dispersion and focusing properties of the mass spectrometers with magnetic focusing prisms were studied experimentally. The rational versions of focusing systems which form the ion beams of specified configuration at the input of the magnetic prism with the r^{-1} inhomogeneous magnetic field were determined. The influence of the ion beam parameters on the analytical characteristics of the magnetic mass spectrometer with the electrical ion focusing by the direction was investigated. The physical and technical features and application area of mass spectrometers and mass spectrographs with the magnetic focusing prisms were considered.

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