Proceedings of the International Conference Nanomaterials: Applications and Properties
Vol. **3** No 2, 02MAN09(3pp) (2014)

Prism Magnetic Mass Analyzer with Parallel Ion Beam

O.S. Kuzema[1,*], P.O. Kuzema[2,†]

[1] *Sumy National Agrarian University, 160, Kirov Str., 40021 Sumy, Ukraine*
[2] *Chuiko Institute of Surface Chemistry of NAS of Ukraine, 17, General Naumov Str., 03164 Kyiv, Ukraine*

(Received 11 July 2014; published online 29 August 2014)

It has been determined the ion-optical properties and characteristics of prism mass analyzer with sector inhomogeneous magnetic field r^{-1} in presence of two electrostatic ion focusing systems one of which is situated before the prism, and another one – after it. It has been shown the possibility of formation and focusing of parallel ion beam in the mass spectrometer which, in turn, allows one to reduce spherical aberrations of the additional focusing system.

Keywords: Ion beam, Mass analyzer, Ion-optical system, Matrix, Electrostatic lens.

PACS number: 07.75. + h

1. INTRODUCTION

Ion-optical properties of prism mass analyzers with the magnetic field r^{-1} are well-studied and it is determined their advantages in the case of both magnetic [1-3] and electrical [4-6] ion focusing by the direction. Upon this, it is found that in prism mass analyzers with single focusing it is sensible to use electrical focusing of ions by their moving direction since, in comparison with the magnetic one, it allows increasing the dispersion of a mass analyzer, reducing the influence of prism end fields and ion beam charge on the characteristics of a mass analyzer, as well as simplifying the requirement for accuracy of manufacturing of prism magnetic poles and for relative position of ion-optical system nodes. Practical realization of the mass analyzer with electrical ion focusing by the direction is carried out by means of using the focusing system situated between the ion source and magnetic prism. At the same time, functional capabilities of the mass analyzer may be extended if one equips its ion-optical system with additional focusing system placed between the magnetic prism and ion collector. Such a device is studied in this work.

2. ANALYSIS OF LATEST INVESTIGATIONS AND PUBLICATIONS

For the last years the studies of the possibility for practical application of prism mass analyzers with sector inhomogeneous magnetic field r^{-1} have attracted much attention of physicists and engineers of ion-optical devices and microprobe equipment. In published studies it has been shown that in such magnetic field the ion focusing by the direction can be achieved in several ways, namely by means of a curvilinear boundary of prism magnetic field [7, 8], or by using additional homogeneous magnetic field [9], or by the use of electrostatic lenses or lens system in the case when the boundary of the magnetic prism is straight [10]. It should be noted that electrical ion focusing by the direction extends the choosing range of physical and geometric parameters of a mass analyzer, which opens the additional possibilities to optimize its main characteristics. In the system with double focusing it was achieved the record resolution for the present day owing to use the magnetic field r^{-1} [9]. The influence of the electrostatic focusing systems aberrations on the characteristics of prism mass spectrometer was studied in the work [11] and it was shown that application of multilens focusing systems with corrected spherical aberration improves essentially the resolution and sensitivity of the mass spectrometer. Thus, the results of investigation of prism mass analyzers with spherical ion beam focusing indicate that their use in the devices and equipment for the materials analysis is advisable.

However, in view of recent studies and publications on the development and application of prism mass analyzers it is seen that multilens ion focusing systems based on quadrupole-octupole lenses [12] are much harder to manufacture and control than systems with single axisymmetric electrostatic lenses. Therefore there is a need for the application of simple single-focusing systems in mass analyzers, and the spherical aberrations are to decrease by forming a parallel ion beam which, after separation by the masses in a magnetic prism, is focused by additional electrostatic lens. The aim of this study is to determine the ion-optical properties and characteristics of the prism mass analyzer with additional focusing system.

3. RESULTS AND DISCUSSION

Advanced prism mass analyzer, ion-optical scheme is shown on Fig. 1, operates in the following manner: from the ion source 1 the ion beam 2 having the appropriate divergence angle comes to the first focusing system 3 which from divergent ion beam forms parallel ion beam. Further, this beam reaches the magnetic field of the prism 4 and it is divided there by the masses on separate components which differ by ion mass-to-charge ratio. After the magnetic prism the parallel ion beam of selected mass is focused by the additional electrostatic system 5 onto the ion collector 6 and is registered. Selection of incoming to the additional focusing system 5 after the

* nikonorov@ukr.net
† sci-worker@yandex.ua

magnetic prism 4 ions of one mass or another is realized by changing the magnetic field value with special device which is not shown on Fig. 1.

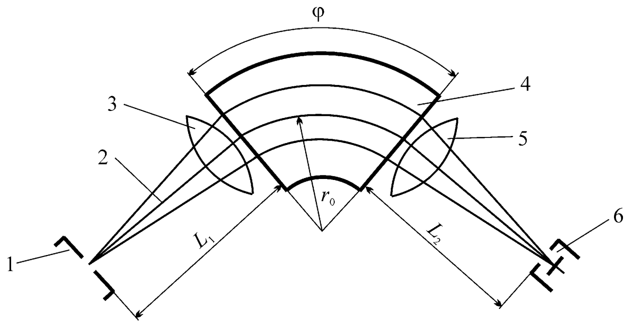

Fig. 1 – Ion-optical scheme of the mass analyzer: 1 – ion source, 2 – ion beam, 3 – first focusing system, 4 – magnetic prism, 5 – additional focusing system, 6 – ion collector.

Before determining the ion-optical properties and characteristics of the mass analyzer it should be noted that ion moving trajectories in considered ion-optical system are described by linear differential equations, therefore this system can be considered as the device performing linear transformation of the initial parameters of trajectory to the final ones, and matrix apparatus can be used to describe such transformation. For this, the ion trajectory should be divided into separate sections, each of which corresponds to the transformation matrix, and then by successive multiplication of matrices for ion trajectory sections one will obtain the full transformation matrix for all ion-optical system of the mass analyzer and determine its properties and characteristics. Taking into account that the prism magnetic field does not possess dispersive properties, we will determine the ion-optical properties of the mass analyzer only in radial plane and in linear approximation.

While finding a complete transformation matrix of ion trajectory parameters let's use the following assumptions: we assume that thin electromagnetic lenses are used as the focusing systems, because the length of their electric field is much smaller than the focal length, and both lenses are adjacent to the boundaries of the magnetic prism. Magnetic leakage fields on input and output prism boundaries we calculate by replacing the real magnetic field with the ideal one equivalent to the angle of ion deflection in the prism. We also assume that the boundary of the prism is straight, and the central ion trajectory is perpendicular to it.

Three-dimensional matrix transformation that describes the relationship between the initial and final parameters of the ion trajectory in the radial plane can be represented as:

$$\begin{pmatrix} y_5 \\ y_5' \\ \mu_5 \end{pmatrix} = M_5 \cdot M_4 \cdot M_3 \cdot M_2 \cdot M_1 \begin{pmatrix} y_0 \\ y_0' \\ \mu_0 \end{pmatrix} = M \begin{pmatrix} y_0 \\ y_0' \\ \mu_0 \end{pmatrix}, \quad (1)$$

where y_0, y_0', μ_0 – the initial parameters of the ion trajectory at the ion source output: initial shift in the units of central trajectory radius r_0, direction, and relative change of the ion impulse, respectively; M_i – transformation matrix for the appropriate section of the ion trajectory; y_5, y_5', μ_5 – the final parameters of the ion trajectory in the plane of collecting gap of the ion source.

Ion-optical system of the mass analyzer has two sections of ion free flight, for which the matrices have the form

$$M_1 = \begin{bmatrix} 1 & l_1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \; M_5 = \begin{bmatrix} 1 & l_2 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

where $l_1 = \dfrac{L_1}{r_0}$, $l_2 = \dfrac{L_2}{r_0}$ (see Fig. 1).

The matrices for the first and second lens are:

$$M_2 = \begin{bmatrix} 1 & 0 & 0 \\ -\dfrac{1}{f_1} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \; M_4 = \begin{bmatrix} 1 & 0 & 0 \\ -\dfrac{1}{f_2} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

where $f_1=F_1/r_0$, $f_2=F_2/r_0$ – focal distance of lenses in the units of central ion trajectory radius.

The matrix for the prism with magnetic field r^{-1} was obtained in [10] and it has the form

$$M_3 = \begin{bmatrix} 1 & \phi & \dfrac{\phi^2}{2} \\ 0 & 1 & \phi \\ 0 & 0 & 1 \end{bmatrix} \quad (3.1).$$

The full matrix M for transformation of initial parameters of the ion trajectory into the final ones is determined by gradual multiplication of matrices for individual sections of the ion trajectory

$$M = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}, \quad (3.2)$$

where $a_{11} = \left(1 - \dfrac{l_2}{f_2}\right) - \dfrac{1}{f_1}\left[\left(1 - \dfrac{l_2}{f_2}\right)\phi + l_2\right]$;

$$a_{12} = \left(1 - \frac{l_2}{f_2}\right) l_1 - \frac{l_1}{f_1}\left[\left(1 - \frac{l_2}{f_2}\right)\phi + l_2\right] + \left(1 - \frac{l_2}{f_2}\right)\phi + l_2;$$

$$a_{13} = \left(1 - \frac{l_2}{f_2}\right)\frac{\phi^2}{2} + l_2\phi; \; a_{21} = -\frac{1}{f_1}\left(1 - \frac{\phi}{f_2}\right) - \frac{1}{f_2};$$

$$a_{22} = -\frac{l_1}{f_2}\left(1 - \frac{\phi}{f_2}\right) - \frac{l_1}{f_2} + \left(1 - \frac{\phi}{f_2}\right); \; a_{23} = \phi - \frac{\phi^2}{2f_2};$$

$$a_{31} = a_{32} = 0; \; a_{33} = 1.$$

Knowing the matrix elements a_{ij}, we can write the expression for the deviation of the ion with arbitrary initial conditions from the central trajectory in the plane of the collecting gap and define the basic parameters of the ion-optical system of the mass analyzer. In accordance with (3.1) and (3.2), the deviation of the ion with the final parameters of trajectory can be written as

$$y_5 = a_{11}y_0 + a_{12}y_0' + a_{13}\mu_0 . \qquad (3.3)$$

In the relationship obtained the matrix elements a_{11}, a_{12}, a_{13} define geometric enlargement, quality of the ion focusing, and efficiency of ion separation by impulse, respectively. Let's define first the value of geometric enlargement of the ion-optical system

$$\frac{y_5}{y_0} = a_{11} = \left(1 - \frac{l_2}{f_2}\right) - \frac{1}{f_1}\left[\left(1 - \frac{l_2}{f_2}\right)\phi + l_2\right]. \qquad (3.4)$$

Taking into account that $y_5 = Y_5/r_0$, $y_0 = Y_0/r_0$, $l_2 = L_2/r_0$, $f_1 = F_1/r_0$, $f_2 = F_2/r_0$, we will have

$$\frac{Y_5}{Y_0} = \left(1 - \frac{L_2}{F_2}\right) - \frac{r_0}{F_1}\left[\left(1 - \frac{L_2}{F_2}\right)\phi + \frac{L_2}{r_0}\right]. \qquad (3.5)$$

Parallel ion beam comes to the input of additional lens, so in order to focus it onto the entrance gap of the ion collector it is necessary for the focal length F_2 of the additional lens to be chosen equal to the distance L_2 from the ion collector to the prism. Then from (3.5) we obtain:

$$\frac{Y_5}{Y_0} = -\frac{L_2}{F_1}. \qquad (3.6)$$

We will determine the condition of ion focusing by the direction if the relationship (3.3) does not depend on the initial angle of ion beam divergence y_0'. This is possible when $a_{12} = 0$. Thus, this condition will be

$$\left(1 - \frac{l_2}{f_2}\right)l_1 - \frac{l_1}{f_1}\left[\left(1 - \frac{l_2}{f_2}\right)\phi + l_2\right] + \left(1 - \frac{l_2}{f_2}\right)\phi + l_2 = 0 \qquad (3.7).$$

Or:

$$\left(1 - \frac{L_2}{F_2}\right)\frac{L_1}{r_0} - \frac{L_1}{F_1}\left[\left(1 - \frac{L_2}{F_2}\right)\phi + \frac{L_2}{r_0}\right] + \left(1 - \frac{L_2}{F_2}\right)\phi + \frac{L_2}{r_0} = 0 \qquad (3.8).$$

In order to form the parallel ion beam by the first lens it is necessary to fulfill the condition $F_1 = L_1$, and in order to focus this beam after prism by the additional lens it is necessary, as noted above, that $F_2 = L_2$. In this case the matrix element $a_{12} = 0$, i.e. ion focusing by the direction is realized in the ion-optical system of prism mass analyzer, and geometric enlargement at the symmetrical design of the device ($L_1 = L_2$) is equal to unity.

The dispersion properties of the mass analyzer are determined by the matrix element a_{13}. Dispersion $D = r_0 a_{13}/2$, i.e.

$$D = \left(1 - \frac{L_2}{F_2}\right)\frac{r_0\phi^2}{4} + \frac{L_2}{2}\phi . \qquad (3.9)$$

On the condition of directional ion focusing by the additional lens the first summand in the relationship (3.9) will be equal to zero and dispersion $D = L_2\varphi/2$. If the additional lens is absent, i.e. $F_2 = \infty$, and ion focusing by the direction is performed by the first lens, then dispersion $D = r_0\varphi^2/4 + L_2\varphi/2$.

4. CONCLUSION

Based on the analysis of the research and the results, it can be stated that the ion-optical properties and characteristics of prism mass analyzer with sector magnetic field r^{-1} demonstrate the feasibility of such a device in mass spectrometers and microprobe instruments. Advantages of the mass analyzer with electrical ion focusing by the direction of its movement give the possibility to use ion sources with large output current and beam divergence angle, thereby increasing the sensitivity and accuracy of analytical instruments and equipment which uses ion beams. Despite the increased dispersion in the absence of additional focusing system, prism mass separator with parallel ion beam can be useful in the development and application of simple ion-optical devices for technological purposes.

REFERENCES

1. K. Zigban, *Alpha-, Beta-, and Gamma-Spectroscopy* (Moscow: Atomizdat: 1969).
2. A.F. Malov, V.A. Suzdalev, E.P. Fedoseev, *Zhurnal Tekh. Fiz.* **35** No5, 914 (1965).
3. N.A. Shekhovtsov, *Magnetic Mass Spectrometers* (Moscow: Atomizdat: 1971).
4. A.S. Kuzema, N.S. Zinchenko, O.R. Savin, *Zhurnal Tekh. Fiz.* **47** No11, 2368 (1977).
5. A.S. Kuzema, A.D. Pogrebnyak, P.O. Kuzema, *J. Nano-Electron. Phys.* **2** No1, 69 (2010).
6. USSR A.C. 270330, *Mass Spectrometer* (N.A. Shekhovtsov, P.P. Barzilovich, A.S. Kuzema, O.R. Savin, I.Ya. Chertkov, V.F. Shkurdoda), publ. 08.05.1970.
7. E.P. Fedoseev, *Zhurnal Tekh. Fiz.* **38** No8, 1320 (1968).
8. N.A. Shekhovtsov, V.F. Shkurdoda, A.S. Kuzema, A.S. Koloskov, *Atomnaya. Energia.* No22, 506 (1964).
9. H. Matsud, S. Fucumoto, M. Nojiri, *Zeitschrift für Naturforschung A.* **21** No1, 25 (1966).
10. A.S. Kuzema, O.R. Savin, I.Ya. Chertkov, *Analyzing Systems of Magnetic Mass Spectrometers* (Kiev: Naukova dumka: 1987).
11. A.S. Kuzema, A.E. Solov'yova, *Visnyk SNAU.* **1** No17, 156 (2008).
12. E.V. Shpak, S.Ya. Yavor, O.R. Savin, A.S. Kuzema, *Zhurnal Tekh. Fiz.* **39** No9, 1720 (1969).