5.6 Mass Spectrographs

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5.6.1 Construction and Calculations

by H. Ewald

In recent years, German physicists have been making increasing use of both mass spectrographs in the stricter sense (precision instruments for the determination of masses and relative isotopic abundances, using photographic plates) and mass spectrometers, which can only measure relative isotopic abundances, and use electrical methods of measurement.

W. Paul[87] (Göttingen) has built an all-metal mass spectrometer which can be baked out. As in Nier's most recent instrument, the rays are deviated 60° in the magnetic field, and have an average radius of curvature of 20 cm. The entrance and target slits are 34.7 cm away from the boundary planes of the fields, and are imaged upon each other in a ratio of 1:1. D, the mass dispersion in the plane of the target slit, is $D = 40/M$. If we accelerate the ions with a potential of $U = 1600$ volts and assume an uncertainty of $\Delta U = 5$ volts, an entrance slit-width of 0.2 mm would give a resolving power of about 300. Those walls of the magnetic deflection chamber which are perpendicular to the magnetic flux are of magnetically permeable iron, and also serve as pole-pieces. The other walls are made of a non-magnetic V2A steel (V2A supra), and are electrically welded to the pole-pieces. V2A tubes with an unobstructed internal diameter of 35 mm are welded to the entrance and surface. The ends of these tubes contain the slits, ion source and targets. Glass caps, fused

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87. W. Paul, Z. Physik (in press).

to rings of 0.1 mm silver foil, fit against flanges at the ends of these tubes, and also carry the high-voltage leads. Dispite baking out, the iron continued to give off more CO than could be tolerated, so that a separate deflection chamber was provided for the investigation of light gases. This chamber consisted of a copper tube 35 mm wide, suitably bent in the middle, and plated with gold on the inside.

In order to obtain sufficiently high ionic currents even at low gas densities, a Heil[88] ion source was used. In this source, the ions are given velocities of 100-150 volts by collision with oscillating electrons. In order to keep these electrons from colliding with the anode prematurely, they are guided by a magnetic field of a few hundred Gauss. The ions are drawn out of the source with a potential of 10-30 volts, accelerated to 1600 volts, and then focused on the entrance slit by means of a suitable optical arrangement. At first, it was found that a change in the oscillating magnetic field of the ion source influences the results obtained for the ratios for the components of mixtures. This was due to pre-dispersion of the ion beam in this field. This trouble was cured by using smaller field strengths, and by magnetically shielding the ion source by surrounding it with a tube of Hyperm. The slit-widths were usually a few tenths of a millimeter; the ionic current of the principal isotope was usually about 10^{-10} amp.

The first tests of the spectrometer were carried out with the elements rubidium, potassium and thallium, whose ions can be generated with homogeneous velocities by means of hot anode[89]. In this case, defects in the ion source

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88. H. Heil, Z. Physik 120, 212 (1943).
89. W. Walcher, Z. Physik 121, 604, (1943).

cannot cause broadening of the lines. After the instrument has been throughly been baked out, the theoretical line-width was obtained. The oscillating ion source was tested by using it to make a mass spectrogram of neon; its operation was quite satisfactory.,

The results obtained with the instrument described in this and subsequent sections are discussed in another place (see section 3.2).

A similar instrument was build by Mattauch and Hintenberger in the Kaiser Wilhem Institute for Chemistry. This was also an all-metal instrument, but somewhat larger and more difficult to construct. Its slit can easily be moved and its ion source adjusted during operation.

The famous Mattauch-Herzog double-focusing mass spectrograph[90] was moved to Berlin-Dahlem at the end of 1938, when Mattauch was called to the Kaiser Wilhem Institute for Chemistry. A large number of relative isotope abundance measurements were made on this instrument in its new location (see 3.2). A good deal of effort was also expended on various tests and improvements in order to find the conditions under which this type of apparatus could meet the high standards of performance imposed by accurate mass determinations, and still operate reliably. The experience thus gained furnished the basis for the construction for the new model built by Ewald[91] in 1941-44. Since the first instrument had proven sound in principle, the optical pattern was retained intact. However, great care was devoted to attaining sufficient

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90. J. Mattauch, Ergebn. exakt. Naturwiss XIX, (1940).

91. H. Ewald, Z. Naturforsch. 1, 131, 1946.

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stability of the optical path, to obtaining the best possible machine work, the best adjustment mechanisms and a good stable vacuum. Furthermore, all delicate and essential parts of the apparatus were easily accessible for cleaning, and could be removed and reinserted into the apparatus without disturbing the optical path. In order to avoid perturbing electrical fields, no insulating, greasy or oily surfaces were permitted in the neighborhood of the optical path. In addition to this, even clean metal surfaces were placed as far as possible from the beam, or were at least easily accessible for cleaning.

All of these requirements seemed to be met best by making the principal parts of the apparatus from massive pieces of forged brass or iron, which were screwed together using rubber washers. The use of soldered joints was avoided as far as possible, since such joints are mechanically weak, and endanger the vacuum. Simmer rings were used in the 18 cases in which it was necessary to have control rods, etc., pass through the wall of the vacuum chamber. Two such rings were placed one in front of the other, suitably oriented, the control rod introduced through them, and the empty space filled with a mixture of vacuum oil and vacuum grease. Ions were generated by means of a gas discharge tube, which could easily be converted to a Dempster high frequency spark tube by exchanging a few of the parts for others. The slit was formed by V2A steel rollers mounted so as to be able to rotate. Along the center section of one of these rollers, the diameter of the cylinder was reduced by an
p. 82 amount equal to the desired slit-width; this cylinder was pressed against the other by means of a spring. In addition to this, the effective slit-width can be varied by swinging the slit holder about an axis which

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coincides exactly with the direction of the slit. If this slit becomes clogged with hydrocarbons from the ion beam, the rollers can be rotated through an angle of 10-20° from the outside during operation, until clean portions of the roller surfaces are in position. Clogging of the slit can easily be checked from time to time by means of a control target. The slit can be moved along and across the axis of the apparatus during operation, and can also be rotated about this axis.

Great care must be devoted to the mounting of the electrical deflection plates. In order to permit easy cleaning of the plates, the plate-holder has been made so that it can be introduced into its housing from the side in a very reproducible position. This is important because of the plate polarization effect, which is unavoidable after a few weeks of operation.

The magnetic field chamber consists of a very heavy brass frame which is attached to the other parts of the apparatus by means of screws. This frame is provided with the necessary openings in the side for the entry of the beam, insertion of the plate, pumping, and so forth. Suitably shaped magnetic pole-pieces are fitted into this frame from above and below, using rubber washers. The distance between the pole-pieces is 5 mm. The inner faces of both pole-pieces are slotted on one side to receive the photographic plate. The plate holder is designed in such a way as to permit vertical motion of the plate in this slot during operation. Thus, in the present case, as many as 7 spectra can be taken in rapid succession by operating only one control. The best setting of the controls can then be judged by examination of these 7 photographs.

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An adjustment necessary for the mutual orientation for the two fields is located between them. It should be pointed out that the only portion of the apparatus which is solidly bedded is the magnetic field chamber; the rest of the instrument, - electric field, head (slit housing and pump supports) and ion tubes - are supported from a large wooden frame - mobile and stress-free - by means of cables, pulleys and counterweights. One of the most important adjustments proved to be the "turner", which permitted the two fields to be rotated with regard to each other about the optical axis during operation. We were quite surprised to observe that the lines were sharpest not when the fields were exactly perpendicular, but when they were inclined to each other at an angle of a few degrees. In order to permit more rapid changing of plates, the magnetic field chamber can be isolated from the pumps and from the rest of the apparatus by two vacuum valves. Figure 22 shows a cross section through the entire apparatus. After testing, the first measurements were made with this apparatus. Very little trouble was experienced with the vacuum. Since the number of adjustments is necessarily large, a certain amount of practice is necessary in judging the sharpness of lines, their possible errors and causes.

p. 84 The sharpness of the lines in the mass spectrograms obtained was close to the particle size of fine-grained plates. Photometrically determined line-widths gave a calculated resolving power M/dM of at least 26,000. Until now, a resolving power of this order has been obtainable only with the oversized mass spectrographs of Jordan.

In order further to increase resolving power and dispersion, a large instrument was planned and begun by Mattauch.

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Figure 22. Horizontal section through the new model of the Mattauch-Herzog double-focusing mass spectrograph (partially schematic).
1: arrangement for introducing and holding plates. 2: external portion of the magnet. 3: photographic plate. 4: iron frame of magnetic field chamber. 5: straight ways. 6: curved ways. 7: turner. 8: insulated leads for the deflection plates. 9: control target for ionic beam. 10: oil diffusion pump Q. 11: precision slit. 12: flat ringed high voltage insulator, flow channel of gas discharge. 13: cross-carriage. 14: water cooling. 15: one of the two high frequency leads. 16: window for observation of spark. 17: vacuum valves. 18: magnetic field diaphragm. 19: oil diffusion pumps P and Q. 20: projection lamp for imprinting a reference point on the plate for use in evaluating plates.

Glossary:
Magnetfeld = magnetic field
Zwischenstück = intermediate section
Elektr. Feld = electrical field
Kopfteil = head
Gasentladungsrohr = gas discharge tube
Funkenrohr = spark tube

In this instrument, an essentially different optical system, based on the theory of double focusing spectrographs given by Herzog[92], Mattauch and Herzog[93] and Herzog and Hauk[94] was used. Calculations for a linear image curve and pole-piece boundary as a special case of the theory were carried out by Klemm[95], who also collected the necessary formulas in the form of a
p. 85 short summary of the general theory. In this case, the deflection of the rays in the magnetic field is 180°, and the plate is therefore placed outside

92. R. Herzog, Z. Physik 89, 447 (1934).

93. J. Mattauch and R. Herzog, Z. Physik 89, 786 (1934).

94. R. Herzog and D. Hauk, Ann. Physik 33, 89 (1938).

95. E. Klemm, Z. Naturforsch. 1, 137 (1946).

the magnetic field. Mass dispersion and resolving power will be three times as great as in the first two instruments. Because of the war, the construction of this new model could not be carried any further, so that only a few parts are in existence at the present time.

Herzog[96] has calculated and discussed the paths of charged particles traversing an ideal plane condenser, whose field is homogeneous up to the edge, and then is bounded by a sharp change in potential. In addition to the deflection, there is a cylindrical lens action; Herzog determines the position of the focal and principal points. In mass spectrography, the plane condenser can also be used in place of the cylindrical condenser. It has the advantage of being easier to make, but has the disadvantage that high deflection potentials are usually necessary. Rochnagel[97] and Glaser[98] have indepently recognized that a deflection condenser has the properties of an optical cylindrical lens. Both calculated thelens properties of the arrangement assuming an arbitrary Laplace field. We need merely mention here that certain results obtained by Herzog did not agree with the corresponding results obtained from the formulas of Rochnagel.

In another theoretical paper, Herzog[99] investigated the electron - optical cylindrical lens effect of the stray field of a condenser in order to evaluate the extent of the error committed by assuming the boundary of the field, whose length did not in general correspond to the length of the

96. R. Herzog, Z. Physik, 113, 166, (1939).
97. A. Rochnagel, Z. Physik, 111, 537, (1938).
98. W. Glaser. Z. Physik, 111, 357, (1939).
99. R. Herzog, Physik Z. 41, 18 (1940).

condenser plates. The method of calculating this length is given in the paper. In exact work, it is necessary to consider an additional cylindrical lens effect which is superimposed on that of the stray fields. In order to picture the effect of the stray fields, the paths of particles in an actual p. 86 condenser are calculated, and compared with those in the "substitute" fields with a change of potential.

5.6.2 Gauss Dioptrics and Image Defect Theory of a Mass Spectrograph[100]

by H. Marschall

The present paper is an effort to lay the foundations for an ion optics, analogous to light and electron optics, which will serve as the basis for future mass spectrographic development. Mass spectrographs have already undergone a good bit of development, and will presumably undergo more, paralleling in many ways the development of optical spectrographs. The present situation is simpler, in that refraction phenomena caused by the wave nature of light are absent. On the other hand, it is still necessary to work out a theoretical basis for treating all lens errors which occur in geometrical optics (aberration, astigmatism, etc.), and to correct "chromatic" image errors, which, in the present case, arise from velocity dispersion. This comprehensive program is only partially realized in the present paper, since the elimination of image errors still has not been accomplished. On the other hand, we have carried out an exact analysis of a double focusing deflector consisting of superimposed electrical and magnetic fields operating on the corpuscular radiation at the same place, without any special assumption as to the structure of the two fields. Stray fields, which are always present, can be taken into

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100. H. Marschall, Physik Z. 45, 1 (1944).

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account in the present case, whereas in Herzog's 1934 paper, which forms the basis for the Mattauch spectrograph, this was not possible. From the standpoint of image formation, the instruments of Herzog and Mattauch[95], Bainbridge and Jordan[101], Dempster[102] and Aston[103] are cylindrical lens systems. By properly shaping the deflecting electrodes and magnetic pole-pieces, a stigmatic system can be obtained; this is important if one wishes to avoid a possible error recently described by Ewald.[103a] In addition to this, we can expect a diminution of some especially annoying image defects. In ordinary optics, the correction of defects means either high resolving power or the possibility of achieving high intensity by means of a large apperture. Similarly, the mass spectrograph, with a narrow slit, can serve as a high resolution precision instrument for determining mass defects; with a wide slit, it can be arranged to serve as a isotope separator. The disadvantage of this apparatus lies in the vignetting of the beam by the condenser plates located between the pole-pieces, so that only a rather restricted range of masses (in practice, approximately $\triangle M/M$ = ± 8%) reaches the photographic plate.

p. 87 Since the deflection field has a lower degree of symmetry than the rotationally symmetrical imaging system, there are also image defects of lower order: in place of the 3rd order image defects occuring in the case of rotationally symmetrical image-formers, we now have second order image defects. This requires the working out of a new system and terminology of image defects, and also means that our images will be of poorer quality than we are used to in images formed by rotationally symmetrical lenses, insofar as we are unable to correct our system.

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101. T. Bainbridge and E. B. Jordan, Physical Review 50, 282 (1936).

102. A. J. Dempster, Physical Review (2)51, 67, 1937.

103. S. W. Aston, Proc. Roy. Soc. (London) series A, 163, 391 (1937).

103a. H. Ewald, Forsch, 2, 384 (1947).

3.6.2.1 Carrying out the process.

The two sketches in figure 23 show the pole-piece and the electrode arrangement of the deflecting field. In the actual instrument, the deflection electrodes are located between the pole-pieces.

Figure 23. The electromagnetic deflection field and its relationship to the coordinates u, v and w. The left-hand sketch shows the arrangement of the pole-pieces of the deflecting magnets, whereas the right hand sketch shows the arrangement of the electrodes for the creation of a radial electric field. The definitions of Spaces I, II, and III can be seen from the figure.

Raum = space
Gegenstandsraum = object space
Bildraum = image space

The ion source and the spectrometer slit are in Space I (object space), whereas the photographic plate (or Faraday Cage) serving for the collection of the ionic beam, is located in Space III(image space). No field exists in either space up to the neighborhood of the two boundary planes separating them from the deflecting space. The assignment of the rectangular coordinates u, v and w can be seen from figure 23. The particles move from the object space through the deflection space into the image space in the neighborhood of the v axis, which, in the deflection space, is identical with the circular arc R = constant. The v axis is obviously a symmetry axis of the deflection field; the (scalar) potentials φ and ψ of the electric and magnetic fields have the symmetry properties

as we can see from figure 23. No other assumptions need be made at present concerning the deflection field. Both fields can then be represented by the power series

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The series coefficients E_1, E_2, E_3, E_0, H_1, H_2 and H_3 are functions of v; E_0 has the dimensions of a potential and E_1 and E_2 are field strengths. Primes represent derivatives with respect to v. ϕ and ψ obey the potential laws $\Delta\phi = 0$, $\Delta\psi = 0$. The stray fields in the object and image spaces can be represented in with the help of the above power series by letting R go to infinity. A closer examination shows that convergence of the series in the deflection space depends only on coordinates u and v, which are assumed to be small, whereas the coefficients in the series for spaces I and III decrease along with u and v. In addition to this, E_0 can almost be made to vanish within the deflection field if the deflecting electrodes are at equal but opposite potentials (symmetrical voltage supply). Although the field strengths E_0, E_1, E_2, H_1 and H_2 are already present in Gauss dioptrics, the coefficients E_3 and H_3 are found only in image defect theory.

The equations of motion can be obtained from Fermat's principle, which has been formulated for electron optics by Glaser[10b]. If the mass dispersion $\gamma = \Delta M/M_0$ and the velocity dispersion $\beta = \Delta V/V_0$ are referred to a "normal particle" of mass M_0 and velocity V_0, then the equations of motion contain the coordinates u and v, their derivatives u', v', u'', v'', and the dispersion terms β and γ as well. In many practical cases, these quantities are so small that it is permissible to retain only the linear terms of the series. One then obtains the first approximation to the motion of the ions, that is the ion - optical analog to Gauss dioptrics, which is sufficient to calculate the geometrical optics constants (focal length, image and object distances, dispersion, etc.) of the deflection field. An extension of the progress (inclusion of the quadratic terms) will give the image defects in

10b. W. Glaser, Z. Physik 80, 451 (1933).

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the sense of geometrical optics.

5.6.2.2 <u>Gauss Dioptrics</u>

The equations of motion illustrate the well-known fact that the ionic beam is split up in the deflection space on the basis of mass and
p. 89 velocity, the v coordinate being the only one depending on these two parameters. In spaces I and III, the paths of the particles are independent of γ and / to a first approximation. Particles of different masses but of equal velocities, all of which leave the image plane at its intersection with the v axis, describe different paths in the deflection space and, consequently, in the image space; this can be seen in figure 24. In optics, a light ray with these initial conditions is called an optic axis. If we retain this term, we thus define a separate optic axis for each ionic mass; this axis will serve as a reference for the beam composed of that particular type of particle. The optic axis is thus defined as a special solution of the equations of motion.

A particle which enters the deflection field in the immediate neighborhood of the v axis will continue along very close to the arc R = constant if equilibrium obtains there between electromagnetic forces and the centrifugal force. This requirement determines the ratio of the field strengths E_1 and H_1 up to terms which are first order in the sense of the above terminology. If we also require the ionic paths to be independent of the velocity dispersion (velocity focusing), the absolute values of both field-strengths are also determined.

Figure 24. Definition of the optic axis and its dependence on ionic mass.

Glossary (see caption figure 25)

Gegenstandsebene = object plane

Optische Achsen, etc... = optic axes for two different ionic masses.

In the general case, the deflecting field has the focal properties of a cylindrical lens; however, by specially choosing the ratio of the coefficients H_2 and E_2, it is possible to construct the deflecting field in such a way as to obtain the Gaussian approximation of a stigmatic image of the object plane in the image plane. Stigmatic representation can be obtained with various combinations of the two fields - see figures 25a and 25b -, since it is only the ratio of the two coefficients and not their absolute values, which is fixed. This freedom in the choice of absolute values may be of use in diminishing some particularly annoying image defects. In the following treatment, we will assume a stigmatic deflection field. All the geometrical optics constants of the deflection field can be obtained in a formal manner by using two fundamental solutions of the path equations. In order to obtain quantitative information, the functions $H_0(v)$, $H_1(v)$, $H_2(v)$, $E_1(v)$, and $E_2(v)$ must be known. If the deflection angle is large enough so that the ratio of the arc R to the distance d between the deflecting electrodes is not too small ($R\theta/d \geq 10$) the stray field will have no noticeable influence on the path of the particles. We can then makecalculations which will be valid to a good degree of the approximation on the basis of the assumption that the electromagnetic field exists only with the deflection space, (sharp cut-off of field).

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The field coefficients then vanish in the object and image spaces, and are constant in the deflection space; in particular, $E_0 = 0$. In this case, the paths of the ions can be represented by trigonometric functions. If V represents the lateral magnification of the deflection field (as in geometrical optics, $V < 0$ for real images) and if S is the width of the spectrometer slit in the v direction, the upper limit for the resolving power is then given by

$$D = 1/(\gamma_1 - \gamma_2) = R(1 - V)/SV.$$

where $\gamma_1 = (M_1 - M_0)/M_0$ and $\gamma_2 = (M_2 - M_0)/M_0$, and thus $\gamma_1 - \gamma_2 = (M_1 - M_2)/M_0$.

Figure 25. Two examples of stigmatic electromagnetic deflection fields. Both figures show the electric and magnetic contours in a plane v = constant. a) homogeneous magnetic field, parabolic electrical lines of force. b) electrical field of a cylindrical condenser, hyperbolic magnetic lines of force.

The resolving power is adjusted so that the slit images corresponding to γ_1 and γ_2 coincide. Although small values of V would appear to favor attainment of the greatest possible dispersion, the magnification should not be made too small, in order to avoid making the instrument too long. L, the distance between the object plane and the image plane, is given by

Although it is possible to keep L small by choosing Θ properly, this requires deflection angles of almost 90°, which are too large from the standpoint of vignetting. The L for a given mass can be estimated by measuring the distance from the optical axis to the v axis at the end of the deflection field; this value is $v_A = \gamma R(1 - \cos\Theta)$. After deciding on the magnet and the slit, Θ

is usually the next thing chosen. For a given deflection angle, the smallest length for the magnification V = - 1 is

The object and image spaces are then at equal distances from the deflection field.

If we assume the "chopped-off" field, and use Mattauch's arrangement of the field of the cylindrical condenser and the homogeneous magnetic field, Herzog's presentation agrees indentically with the Gauss approximation.

5.6.2.3 The Image Defects of the Deflection Field.

If the equations of motion are expanded to include second order terms, the differential equations representing Gauss optics are replaced by corrected equations which must be solved by perturbation methods. One then obtains deviations from Gauss optics; i.e., the image defects of the deflection field. Since the optical axes defined in the Gauss dioptrics are solutions of the equations of motion, their course will also be corrected by the perturbation calculations. We must therefore distinguish between true image defects, - i.e. distortion and fuzziness of the slit images of the various masses, - and axis errors.

Although an exact calculation of the image errors requires a knowledge of the stray fields, these have not been considered in the present short account, since simple considerations show that a good estimate of the error can be arrived at assuming the "chopped-off" deflection fields.

a) Image errors of the optical axis. Because of the symmetry properties of the deflection field with regard to the vw plane, which contains the optical axes, deviations occur only in the v direction. If η_A is the coordinate of the optical axis belonging to γ, measured in the image plane, we will expect deviations $_A$ which are porportional to η_A^2, γ^2 and $\eta_A \gamma$. Since, in addition, velocity focusing no longer obtains in the second approximation, there are other correction terms which increase with β^2, $\beta\eta_A$ and $\beta\gamma$.

p. 92 The individual errors of the optical axis are then:

1. Axis - dependent distortion.......................... $\Delta\eta_A = A_A \eta_A^2 V$
2. Mass - dependent distortion.......................... $= B_A \gamma^2 V$
3. Mass - and axis - dependent distortion............ $= C_A \gamma_A \eta_A V$
4. Velocity - dependent aberration..................... $= D_A \beta^2 V$
5. Velocity - and axis - dependent astigmatism...... $= C_A \beta \eta_A V$
6. Velocity and mass - dependent astigmatism........ $= D_A \beta\gamma V$

These errors have been named by analogy with optical image defect theory. Correction terms which are functions of the image coordinates only are designated as distortions; those which are independent of the image coordinates are designated as aberrations; others, showing a mixed dependence, are represented as astigmation. Assuming sharp cut-off of the deflection field, coefficients for all the errors (A_A, ...D_A) can be calculated by elementary integration (integrals over Gauss paths).

The first, second and third distortion defects do not diminish the resolving power of the apparatus; they merely distort the mass scale, and their effect on the experimental measurements can be avoided by suitable calibration. The remaining errors do diminish the resolving power; the intersection of the optical axis with the image plane is no longer a mathematical point, but a short line which increases with β. If the velocity dispersion is small, no diminution of the resolving power by axis errors need be feared.

b) Image errors of the spectrometer slit image

If x and y are the coordinates of the spectrometer slit in the object plane, and

and those of the image, the radius, and the angular coordinates of the aperture diaphragm defining the ionic beam, we may expect deviations from the ideal Gauss image which will be porportional to x^2, y^2, xy, $x\eta_A$, $y\eta_A$, $x\gamma$, $y\gamma$, σ^2, $\gamma\sigma$, $\eta_A\sigma$, $\beta\sigma$, $x\sigma$, $y\sigma$, βx and βy. The individual image defects for the stigmatic deflection field are as follows:

1. Position - dependent distortion.............. $\Delta\xi = A'xyV$

   $\Delta\eta = (A_1x^2 + A_2y^2)V$

2. Position - and axis - dependent distortion.. $\Delta\xi = B'x\eta_AV$

   $\Delta\eta = By\eta_AV$

3. Position - and mass - dependent distortion.. $\Delta\xi = C'x\gamma V$

   $\Delta\eta = Cy\gamma V$

4. Position-dependent aberration................ $\Delta\xi = D_2\sigma^2 \sin 2\alpha V$

   $\Delta\eta = (D_1\cos^2\alpha + D_2\sin^2\alpha)\sigma^2V$

5. Position - and axis - dependent aberration.. $\Delta x = G'\eta_A\sigma\cos\alpha V$

   $\Delta\eta = G\eta_A\sigma\sin\alpha V$

6. Position - and mass - dependent aberration.. $\Delta\xi = K'\gamma\sigma\cos\alpha V$

   $\Delta\eta = K\gamma\sigma\sin\alpha V$

7. Position - and velocity - dependent aberration. $\Delta\xi = L'\beta\sigma\cos\alpha V$

   $\Delta\eta = L\beta\sigma\sin\alpha V$

8. Position - dependent astigmatism............ $\Delta\xi = (H_1x\sin\alpha + H_2y\cos\alpha)\sigma V$

   $\Delta\eta = (H_1x\cos\alpha + H_2y\sin\alpha)\sigma V$

9. Position - and velocity - dependent astigmatism. $\Delta\zeta = P'\beta xV$

   $\Delta\eta = P\beta yV$

p. 93 The terminology is the same as was used for the axis errors. Corresponding to the structure of the deflection field, the correction terms are symmetrical with regard to the ζ coordinate. The first three distortion errors, which do not influence the resolving power of the instrument, can be kept small by having the center of the spectrometer slit coincide with the origin of coordinates x = y = 0 of the object plane. This will also help reduce those astigmatic errors which tend to diminish resolving power. The resolving power is influenced most by the position - dependent aberration, and efforts at image correction should be aimed principally at this error. The error constants A', A_1, A_2, B'... are functions of the field coefficients E_2, H_2, E_3 and H_3, so that it would seem that the image errors can be diminished by properly forming the deflection electrodes and pole-pieces.

5.6.2.4 Some Data for the Practical Planning of a Spectrograph.

These theoretical results were intended for use in the mass spectrograph planned for the research institute of the government installation at Miersdorf, Berlin. A schematic view of the deflector is given in figure 26.

Figure 26. Schematic sketch of the projected Miersdorf mass spectrograph
Isolierplatten = insulating plates
Hilfselektroden = auxiliary electrodes
Umlenkelektroden = deflection electrodes
Magn.Polschuhe = magnetic pole-pieces

The condenser plates K_1 and K_2 are located between the pole-pieces P_1 and P_2 of the magnet. In a space filled with ions, the electrical field should show the smallest possible inhomogeneity at the edges. Since the height of the entire apparatus is limited by the gap between the pole-pieces (4 cm), the electrode gap will be small, and this, in turn, will lead to considerable vignetting. This difficulty is avoided by placing the auxiliary electrodes E at the upper and lower edges of the condenser. These electrodes are kept at a suitable intermediate potential by means of a potentiometer circuit. In practice, these electrodes are mounted in plates of insulating material.

For a radius R = 60 cm, the instrument should have a mass range of $\gamma = \pm 8\%$. Because of vignetting, the deflection angle is chosen to be 45°; in order to keep the instrument as short as conveniently possible, the degree of magnification is chosen to be V = - 1. The resolving power can become very high; to separate two lines whose masses differ by 0.4% (for instance, U^{234} and U^{235}), we can still work with a slit-width of 5 mm, if the worst image errors are actually corrected (use as isotope separator). If the apparatus is constructed with a 0.1 mm slit, the masses 80.007 and 80 can still be separated (mass defect determination). For an acceleration potential of 5,000 volts, a deflection potential of 240 volts at the condenser plates and a magnetic field of $330\ M^{\frac{1}{2}}$ = Gauss (M = mass number) is necessary; for M = 238 (uranium), this comes to about 5,000 Gauss.

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