

April 12, 1960

H. BRUCK

2,932,738

MAGNETIC PRISMS FOR SEPARATING IONIZED PARTICLES

Filed Sept. 7, 1956

2 Sheets-Sheet 1

Fig. 1.

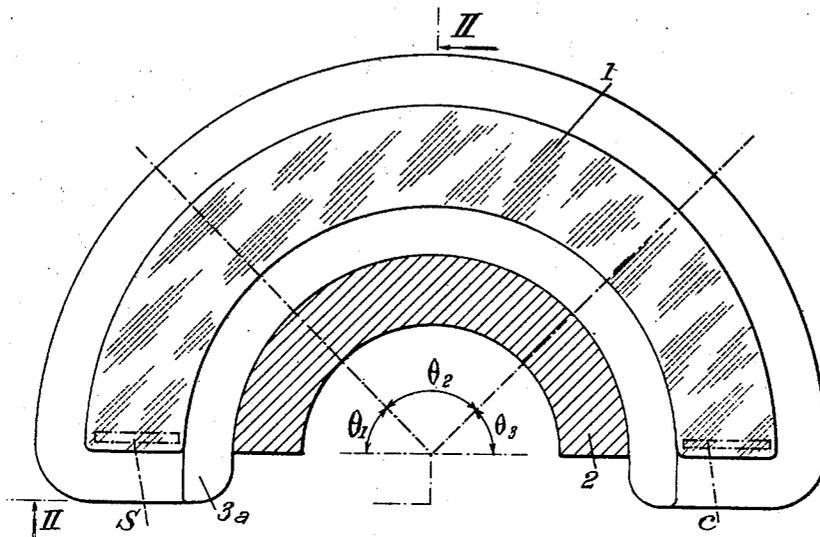
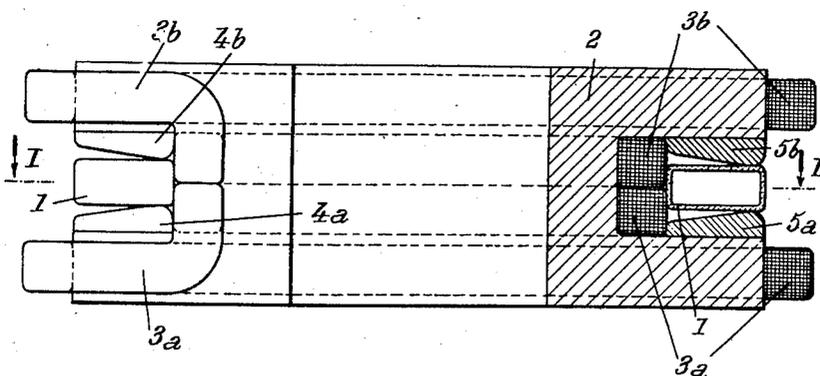


Fig. 2.



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2 Sheets-Sheet 2

Fig. 4.

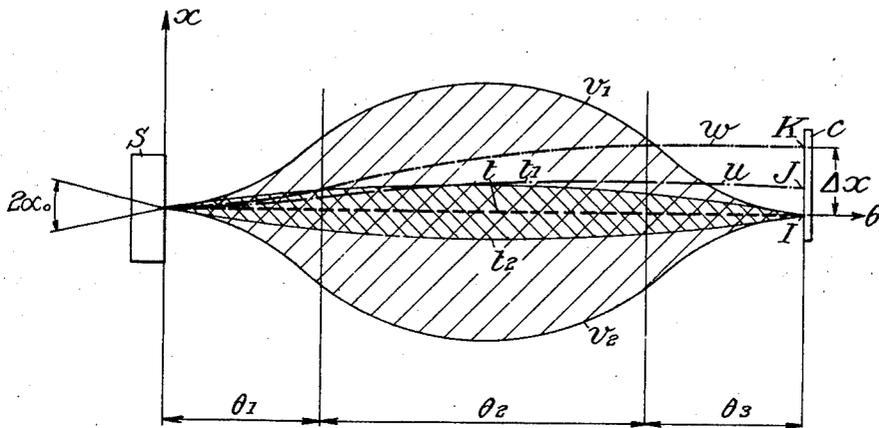
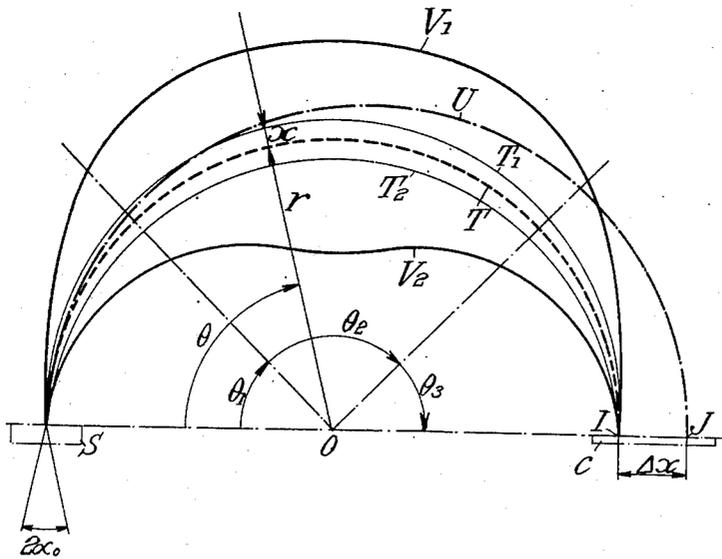


Fig. 3.



1

2,932,738

MAGNETIC PRISMS FOR SEPARATING IONIZED PARTICLES

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The present invention relates to magnetic prisms, that is to say apparatus, such as mass spectrometers, capable of separating ionized particles differing from one another by the value of a given characteristic thereof (mass, charge, velocity or energy), and possibly of measuring said values of said characteristic or of exerting a regulating action upon the source of said particles.

Such apparatus includes as a rule a source capable of emitting a beam of ionized particles into a chamber where the atmosphere is rarefied, an electro-magnet creating a magnetic field capable of bending the path of travel of said particles inside said chamber and collecting means for receiving said particles at the end of said path of travel.

As it is known, the particles for which said characteristic has a selected value are focused on the collecting means at a certain point and the distances between the points of focusing of particles having different values of said characteristics depends upon the differences between said values of said characteristic.

The resolving power of a magnetic prism generally varies similarly to the dispersion thereof, this last term designating the ratio of the displacement of the focus corresponding to a variation of a given characteristic of the particles to the relative value of said variation. The characteristic that is considered is the mass to charge ratio when the apparatus is a mass spectrometer.

The object of my invention is to provide a magnetic prism such that, for given overall dimensions thereof, its resolving power is increased.

For this purpose, according to my invention, the magnetic field serving to bend the path of travel of the ionized particles has a gradient, which is the rate of change of magnetic field intensity with respect to distance, in the direction perpendicular to the mean path of travel of the particles and in the longitudinal mean plane of travel of the particles and this gradient varies along said path so as to have successive values of opposed signs and to increase the dispersion of the particles.

Preferred embodiments of my invention will be hereinafter described with reference to the accompanying drawings, given merely by way of example and in which:

Fig. 1 is a sectional view on the line I—I of Fig. 2 of a magnetic prism made according to my invention.

Fig. 2 is a sectional view of line II—II of Fig. 1.

Figs. 3 and 4 show explanatory curves.

In the following description it will be supposed that the magnetic prism is a mass spectrometer, so that the characteristic according to which the particles are focused is the mass of said particles assuming all the particles have the same charge.

The mass spectrometer includes a source S of ionized particles, a curved chamber 1, collecting means C and an electro-magnet constituted by a magnetic core 2 and a pair of symmetrically disposed excitation windings 3a and 3b (Figs. 1 and 2). Chamber 1 is housed in a groove formed in the periphery of the magnetic core 2,

2

the latter extending over a circular arc generally at most equal to 180°.

In the mass spectrometers known up to this time, the walls of said groove between which chamber 1 is located are in the form of two conical surfaces the generatrices of which make with the middle plane of symmetry of the apparatus a constant angle (which may be zero). In other words the groove walls of spectrometer cores of the prior art are parallel.

In these conditions the deflecting magnetic field has a gradient which is substantially constant from one end to the other of chamber 1. The gradient of the field is the derivative or rate of change with respect to distance thereof in the direction perpendicular to the mean path of travel of the particles and located in the above mentioned middle plane. The mean path of travel between source S and collecting means C, for particles all of which have the same mass value m , is a curve T. Generally this curve is a circular arc having its center at O and the radius of which is r , as shown by Fig. 3, which is similar to Fig. 1 but more diagrammatic.

The whole of the beam emitted from source S with an initial angle equal to $2\alpha_0$ is limited on either side of curve T by two curves T_1 and T_2 and it is focused at I on the collecting means C for all the particles of mass m . In a likewise manner, the particles of the mass equal to $m + \Delta m$ have another mean path of travel U in the form of a circular arc and they are focused at J on the collecting means. The dispersion D, upon which, as above explained, the resolving power depends is

$$D = \Delta x \frac{\Delta m}{m}$$

Δx representing the distance I J.

In Figure 4, I have shown a rectangular coordinate plot of the paths of travel of particles passing through the magnetic field. I have used the radial distance x from the mean path of travel T of particles moving along path T_1 , T_2 , and U as ordinates, and I have used the angular positions of the particles along the paths as abscissas.

I obtain curves t_1 , t_2 and u . Curves t_1 and t_2 limit between them an area which will be hereinafter called "magnetic field area swept by a beam of given angular aperture." The curve corresponding to the mean path of travel T is of course a straight line t . On Fig. 4 the above mentioned area is covered by cross-hatching sloping downwardly toward the right.

My invention is based upon the discovery I have made that the dispersion D is substantially proportional to this area. This is why, in order to increase the resolving power, I make use of a magnetic prism such that the deflecting magnetic field which is to act upon the ionized particles has an alternate gradient (i.e. a gradient which is alternately in one direction and in the opposed direction) such that the area of the magnetic field swept by the beam of particles is greater, other things being equal, than the area between curves t_1 and t_2 . As above stated, what I call an alternate gradient is a gradient (i.e. a derivative as above specified) which varies and in particular changes its sign when moving along the mean path of travel of the particles.

For this purpose the magnetic core 2 is divided into sectors the side walls of which, are alternately convergent toward the center O of the apparatus and divergent from said center as visible on the right and left hand sides of Fig. 2. By way of example, I have shown, on Figs. 1 and 2, a magnetic core which comprises three sectors the angles of which are respectively θ_1 , θ_2 , θ_3 , the angles θ_1 and θ_3 being preferably equal to each other so as to permit a magnification equal to 1. In the case of three sectors, the end sectors must have walls convergent to-

ward the center O of the apparatus, whereas the middle sector is divergent from said center.

Fig. 3 shows the limit trajectories or orbits V_1 and V_2 of the particles of mass m , the mean trajectory T remaining the same in both cases. By plotting on Fig. 4 the radial distances of these limit trajectories V_1 and V_2 from said mean trajectory, I obtain two curves v_1 and v_2 . Likewise by plotting on Fig. 4 the radial coordinates of the mean path of travel for particles having a mass equal to $m + \Delta m$, I obtain a curve w which intersects the collecting means C at K. Curves v_1 and v_2 limit between them the area swept, in a prism having an alternate gradient magnetic field, by a beam of particles having the same aperture $2\alpha_0$ as in the preceding case. This area is indicated by hatchings, the downward slope of which is toward the left. Said area is obviously much larger than that precedingly referred to (hatchings in the opposed direction) and it is found that this increase involves a proportional increase of the dispersion

$$\left(\Delta x \cdot \frac{\Delta m}{m} \right)$$

as indicated by comparison of the segments IJ and IK of Fig. 4.

Advantageously the magnetic core of the apparatus includes a main portion 2 and additional respective pairs of pole pieces fixed to the core in the sectors described hereinabove. The pole pieces 4a and 4b in the end sectors are convergent toward the center O of the apparatus, and in the intermediate sector, the pole pieces 5a and 5b are divergent toward said center O.

If there are more than three sectors the faces of which are alternately convergent and divergent, the choice of the constructional factors (inclination of the faces of the pole pieces, respective angles of the sectors, general shape) will be based upon the comparison of the areas shown by Fig. 4 corresponding respectively to a conventional apparatus having a constant gradient magnetic field and to an apparatus according to the invention. The ideal arrangement for the particular configuration chosen may be determined experimentally. As a matter of fact, it does not suffice to provide an alternate gradient field, but this field must also provide for an increase of the area of the magnetic field swept by a focused beam of particles. Otherwise, a reduction of dispersion might be obtained as it is the case in the construction of synchrotrons.

The above indicated constructional factors may also be calculated by means of algebraic equations indicating:

- (a) the focusing condition and
- (b) the condition for obtaining a given dispersion.

As has been pointed out hereinabove, the resolving power of a spectrograph may be improved by increasing the dispersion of the magnetic prism. The expression for the dispersion of any magnet sector may be expressed as:

$$(1) \quad D_m = \frac{1}{2r} \frac{\Sigma}{2\alpha_0}$$

where:

D_m = the dispersion resulting from a variation in mass.
 r = the radius of curvature of the particle trajectory within the magnetic field.

$2\alpha_0$ = the initial aperture angle in the plane of curvature.
 Σ = the surface in the plane of curvature of the field covered by a beam having an initial aperture angle $2\alpha_0$.

It will be readily apparent from Equation 1 and from the description of Figure 4 given hereinabove that a larger surface corresponds to a larger dispersion. It will further be apparent from the discussion given hereinabove that a core having what may be termed "defocusing" pole pieces 4a and 4b in the sectors defined by angles θ_1 and θ_3 and what may be termed "focusing" pole pieces 5a and 5b in the sector defined by the angle θ_2 produces a larger surface Σ and hence a larger dis-

persion than that produced by a field of constant gradient.

I may also analytically write expressions for dispersion as a function of the inclination or slope of the pole pieces with respect to the plane of the surface Σ . I may express the inclination n of any one of the pole pieces in terms of the radius of the curvature and the magnetic field strength as follows:

$$(2) \quad n = -\frac{r}{\beta_0} \frac{\partial \beta}{\partial r}$$

where β_0 is initial field strength and r is the radius of curvature of the trajectory. It will be obvious that for the end sector pole pieces 4a and 4b the slope n_d is opposite to the slope n_f of the pole pieces in the sector defined by the angle θ_2 .

For purposes of clarity in exposition I will consider symmetrical sectors covering an over-all angle length of 180° . With these conditions it can readily be demonstrated that the following relationship exists:

$$(3) \quad \tan \left[(1 - n_f)^{1/2} \frac{\theta_2}{2} \right] \tanh [(n_d - 1)^{1/2} \theta_1] = \frac{(n_d - 1)^{1/2}}{(1 - n_f)^{1/2}}$$

Similarly, it can be demonstrated that for the dispersion the following expression can be written:

$$(4) \quad \frac{D_m}{r} = \frac{1}{(n_d - 1)} \left[\left(1 + \frac{n_d - 1}{1 - n_f} \right) \cosh ((n_d - 1)^{1/2} \theta_1) - 1 \right]$$

It will be apparent that Equation 4 defines the dispersion in terms of the inclinations of the surfaces of pole pieces 4a and 4b and 5a and 5b. For the conditions given Equations 3 and 4 can readily be solved for any desired value of

$$\frac{D_m}{r}$$

From Equation 1 hereinabove it will be apparent that any increase in dispersion always is obtained at the cost of increased maximum amplitude. At the same time the effective radial distance or width Δr_e within the magnetic field inside the gap, which can be used, decreases for increasing inclination of the pole pieces. It can be demonstrated that the maximum amplitude at the center of the sector is expressed by the relationship:

$$(5) \quad X_{\max} = kr\alpha_0$$

and

$$(6) \quad k = (n_d - 1)^{-1/2} \cos \left[(1 - n_f)^{1/2} \frac{\theta_2}{2} \right] \sinh [(n_d - 1)^{1/2} \theta_1] + (1 - n_f)^{-1/2} \sin \left[(1 - n_f)^{1/2} \frac{\theta_2}{2} \right] \cosh [(n_d - 1)^{1/2} \theta_1]$$

The constant k is the factor by which the amplitude is multiplied with respect to the amplitude reached in a field sector having a uniform gradient.

The effective field region Δr_e , inside which the field strength varies from a very small value up to a very large value, may be expressed by the relationship:

$$(7) \quad \frac{\Delta r_e}{r} \approx \frac{2}{|n|}$$

From Equations 6 and 7 the possible maximum angular aperture may be determined as:

$$(8) \quad (2\alpha_0)_{\max} = \frac{2}{|k|n_f}$$

From the discussion given hereinabove it will be apparent that as the dispersion increases the possible angular aperture decreases. Thus a balance must be achieved between dispersion and intensity.

From the discussion given hereinabove it will be clear that there exists an additional degree of freedom not yet considered. That is, distance above the median plane. This degree of freedom can be disposed of by adding to

5

the conditions set forth in Equations 2, 3, and 4, the symmetry condition that:

$$(9) \quad (-n_f)^{1/2} \tanh \left[(-n_f)^{1/2} \frac{\theta_2}{2} \right] = (n_d)^{1/2} \tan \left[(n_d)^{1/2} \theta_1 \right]$$

Assuming the sectors to be uniformly divergent or convergent, as the case may be, for a mass variation of Δm the displacement of the radius of the equilibrium path from the radius of curvature r may be defined for the respective end sectors and the center sector as:

$$(10) \quad \Delta r_d = -\frac{r}{2} \frac{1}{n_d - 1} \frac{\Delta m}{m}$$

and

$$(11) \quad \Delta r_f = \frac{r}{2} \frac{1}{1 - n_f} \frac{\Delta m}{m}$$

From the foregoing equations the dispersion for a given condition may readily be determined.

While I have described my invention in connection with a sector having an over-all extent of 180°, it applies as well to sectors of other lengths. The increase of dispersion is always proportional to any chosen increase of beam surface inside the field.

In a general manner, while I have, in the above description, disclosed what I deem to be practical and efficient embodiments of my invention, it should be well understood that I do not wish to be limited thereto as there might be changes made in the arrangement, disposition and form of the parts without departing from the principle of the present invention as comprehended within the scope of the accompanying claims.

What I claim is:

1. An apparatus of the type described which comprises, in combination, means forming a chamber under vacuum, a source of ionized particles having different values of a given characteristic thereof, said source being capable of emitting a slightly divergent beam of such particles into said chamber at one point thereof, means located in another part of said chamber for collecting such particles, and an electro-magnet disposed along said chamber for bending the path of said beam between said source and said collecting means, said electro-magnet being such as to give a magnetic field the derivative of which, in the direction perpendicular to the mean path of travel of said particles and located in the longitudinal mean plane of travel of said particles, varies along said path so as to have successive values of opposed signs and to increase the dispersion of said particles.

2. An apparatus of the type described which comprises, in combination, means forming a chamber under vacuum, a source of ionized particles having different values of a given characteristic thereof, said source being capable of emitting a slightly divergent beam of such particles into said chamber at one point thereof, means located in another part of said chamber for collecting such particles, and an electro-magnet disposed along said chamber for bending the path of said beam between said source and said collecting means, said electro-magnet being such as to give a magnetic field the derivative of which, in the direction perpendicular to the mean path of travel of said particles and located in the general longitudinal mean plane of travel of said particles, varies along said path so as to have successive values of opposed signs and to increase the section in said longitudinal plane of a portion of the beam formed by particles having all the same value of said characteristic.

3. An apparatus of the type described which comprises, in combination, means forming a chamber under vacuum, said chamber being in the shape of a portion

6

of an annulus having a longitudinal plane of symmetry and extending along a circular arc located in said plane, a source of ionized particles having different values of a given characteristic thereof, said source being capable of emitting a slightly divergent beam of such particles into said chamber at one end thereof in a direction substantially tangent to said circular arc, means located at the other end of said chamber for collecting said particles, an electro-magnet including a magnetic main core provided with a groove constituting a housing for said chamber, the sections of said magnetic core by planes parallel to said plane of symmetry being circular arcs having their centers on a center line perpendicular to said plane of symmetry and passing through the center of said first mentioned circular arc, energizing windings mounted on said core so as to produce a magnetic field capable of bending the path of said beam along said chamber between said source and said collecting means, said windings running along circular arcs concentric with the corresponding circular arc sections of said magnetic core, and three pairs of pole pieces mounted in said groove between the walls thereof and said chamber, the two pole pieces of each pair being located opposite each other, respectively on opposite sides of said chamber, the three pole pieces on each side of said chamber being disposed end to end along a circular arc concentric with the portion of said core in which they are housed, the inner walls of the pole pieces of the end pairs converging toward said center line, and the inner walls of the pole pieces of the middle pair diverging toward said center line.

4. A mass spectrometer which comprises, in combination, means forming a chamber under vacuum, said chamber being in the shape of a portion of an annulus having a longitudinal plane of symmetry and extending along a circular arc located in said plane, a source of ionized particles of different masses, said source being capable of emitting a slightly divergent beam of such particles into said chamber at one end thereof in a direction substantially tangent to said circular arc, means located at the other end of said chamber for collecting said particles, an electro-magnet including a magnetic main core provided with a groove constituting a housing for said chamber, the sections of said magnetic core by planes parallel to said plane of symmetry being circular arcs having their centers on a center line perpendicular to said plane of symmetry and passing through the center of said first mentioned circular arc, energizing windings mounted on said core so as to produce a magnetic field capable of bending the path of said beam along said chamber between said source and said collecting means, said windings running along circular arcs concentric with the corresponding circular arc sections of said magnetic core, and three pairs of pole pieces mounted in said groove between the walls thereof and said chamber, the two pole pieces of each pair being located opposite each other, respectively on opposite sides of said chamber, the three pole pieces on each side of said chamber being disposed end to end along a circular arc concentric with the portion of said core in which they are housed, the inner walls of the pole pieces of the end pairs converging toward said center line, and the inner walls of the pole pieces of the middle pair diverging toward said center line.

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