

Jan. 26, 1954

J. G. BACKUS
MASS SEPARATOR

2,667,582

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2 Sheets-Sheet 1

Fig. 1

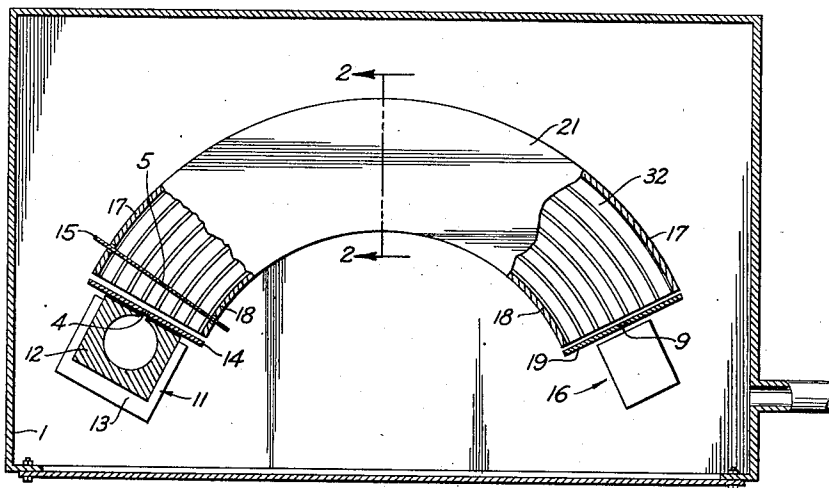
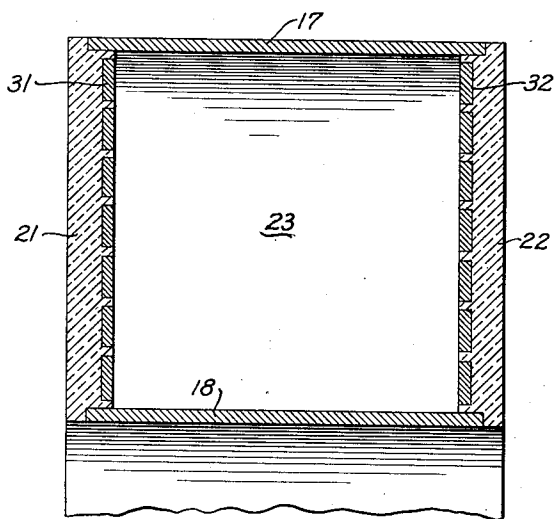


Fig. 2



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Fig. 3

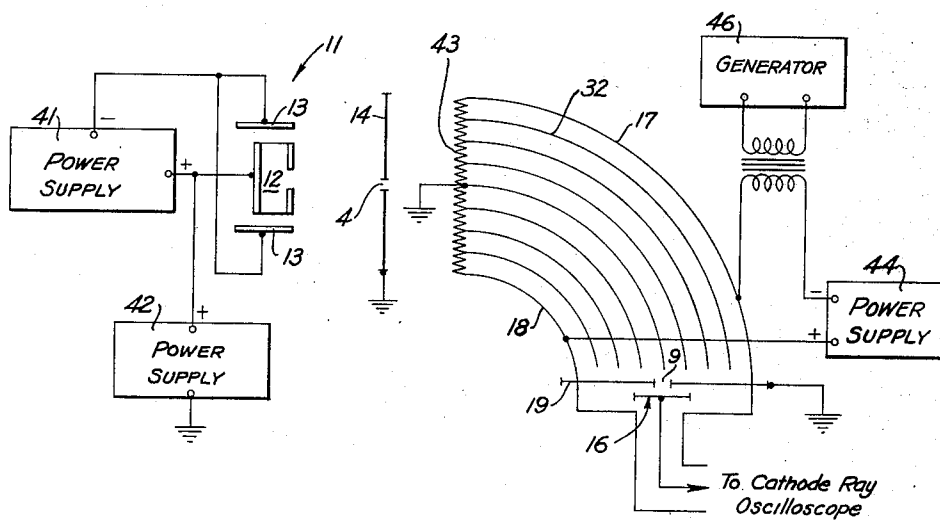
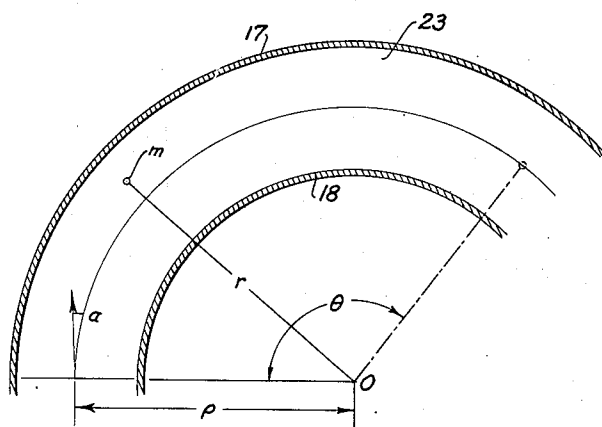


Fig. 4



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MASS SEPARATOR

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7 Claims. (Cl. 250—41.9)

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The present invention relates to arrangements and apparatus for magnetically and electrically influencing a beam of ions in order to resolve the ions into separate, distinguishable groups of like mass-to-charge ratios, and to further provide visual indicia of the value of these ratios as well as the relative abundance of the groups. Such an apparatus may be defined as a velocity-focused mass separator, which term includes mass spectrometers and calutrons.

More or less conventional mass separators have been previously utilized to analyze the gases present in an evacuated space. However, such apparatus is designed to identify only the lighter elements and thus may be made quite small in size. In order to provide satisfactory resolution of any of the elements, light or heavy, numerous hitherto disregarded factors must be considered. Careful observation reveals that a conventional ion source produces ions having an energy variation of from 30 to 50 volts. A practical ion source must combine simplicity and ruggedness. Thus, even though an ion source could be designed having a more uniform ion energy, it would be at the expense of a reduction in the above two prerequisites. In order to obtain satisfactory resolution of heavy elements with such an initial energy spread it would be necessary to use high accelerating potentials and thus large radii of curvature and large magnetic fields if only conventional magnetic focusing were used. Thus to obtain a high quality of resolution and yet maintain a practical size, other means of focusing are necessary.

The proper interaction of electric and magnetic fields will produce a focusing effect sufficient to overcome any of the above-mentioned difficulties. The general principle of this type of focusing was described by Dempster and Bartky in the "Physical Review," volume 33, page 1019, however the instant invention combines a novel arrangement of elements and impressed potentials in order to provide a practical apparatus utilizing this principle.

It is therefore an object of this invention to provide a velocity-focused mass separator.

Another object of this invention is to provide a mass separator having an extremely high degree of resolution of the ion beam.

Another object of this invention is to provide an apparatus suitable for use in the physical analysis of heavy ions.

Another object is to provide in an apparatus of the class described an electric field capable of improving the ion beam focus.

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A further object is to provide an apparatus of the class described utilizing magnetic and electric focusing fields and means to counteract defocusing effects in the region of the source and receiver.

A further object is to provide a mass separator capable of focusing ions having small energy variations.

A still further object is to provide means within a mass separator whereby a divergent ion beam may be focused.

In order to apply the principles of velocity focusing, various factors must be considered, among which are: magnet field strength, electric field strength, and the relative distribution and interaction of the magnetic and electric fields. Certain other practical considerations are also of importance, such as: allowable inhomogeneities of magnetic and electric fields, slope of magnetic and electric fields, and variations in the ion direction, velocity, and mass.

The manner in which the above factors are dealt with is fully discussed in the following description of construction and operation of a mass spectrometer for example, in conjunction with which there are included four figures: Figure 1 is a side view of a simplified schematic representation of the mass spectrometer, showing portions cut away; Fig. 2 is a sectional view of Fig. 1 taken along plane 2—2; Fig. 3 is a diagram of one preferred embodiment of the electrical system associated therewith; and Fig. 4 is a diagram of the apparatus including appropriate reference symbols used in conjunction with the theoretical considerations presented herein.

Referring more specifically to the included drawings, it is to be noted that apparatus proper is contained in a tank 1 which is evacuated. Within the boundaries of the tank 1 a uniform magnetic field is maintained which is perpendicular to the plane of the drawing and directed upward out of the paper. Ions are formed in a conventional ionization chamber 11 comprising an anode 12 and cathodes 13. An accelerating plate 14 including an aperture 4 serves to remove the ions from the source, and a defining slit 5 in plate 15 collimates the ion beam. A receiver 16 serves to collect the ion beam through a collector slit 9 in plate 19. As shown, the receiver 16 is connected to a cathode ray oscilloscope thus providing a pictorial representation of the ion beam; however, various other types of receivers would be suitable, such as a photographic plate for the analysis of radioactive isotopes. Two concentric cylindrical plates 17 and 18 are ar-

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ranged parallel to the magnetic field and disposed on opposite sides of the crescent-shaped region 23 in which an ion beam projected from the ion source 11 to the ion receiver 16 travels. The plates 17 and 18 are mounted upon nonconducting plates 21 and 22 as shown in Fig. 2, thus defining the annular region of ion travel 23.

An electric field is maintained within the region 23 by the application of potentials to the plates 17 and 18, plate 18 being the more positive of the two. Referring to Fig. 4, the ions traversing this region are subject to a magnetic force inward toward the center of their orbit and an electric force outward from the center O. For a particle of mass m and charge e to describe a circular orbit of radius ρ and center O, we must have the centripetal force acting on the particle equal to the difference between the force applied by the magnetic and electric fields, or

$$\frac{mv^2}{\rho} = \frac{Hev}{c} - Ee$$

where

H = magnetic field strength

v = velocity of particle

c = velocity of light

E = electric field strength

from this

$$\rho = \frac{mv^2}{\frac{Hev}{c} - Ee}$$

thus

$$\frac{d\rho}{dv} = \left(\frac{mv^2 He}{c} - 2mvEe \right) \left(\frac{Hev}{c} - Ee \right)^{-2}$$

this will be zero for

$$v = \frac{2cE}{H}$$

Hence a particle entering the field with the velocity given above will describe a circle of constant radius ρ . It may also be noted from the above that

$$\frac{Hev}{c} = 2Ec$$

for a constant radius orbit; that is, the magnetic force inward is twice the electric force outward, which condition may be attained by adjusting the voltage applied to the plates 17 and 18 and the strength of the magnetic field.

The orbit of a particle entering the system with slightly different values of m and V (accelerating potential) from those giving a circular orbit has been calculated, and it has been determined that the foci exist at

$$\theta = \frac{\pi}{\sqrt{2}}$$

or $127^\circ 17'$ which incidentally is the same result as for the purely electrostatic case of a radial electric field. Thus the receiver 16 and source 11 are constructed so as to include an angle of $127^\circ 17'$ therebetween. Furthermore the radial position of the focus varies directly as the mass which is the same as for the 180° magnetic focusing.

Further research on the problem of ion source

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energy variations and initial particle angle leads to the following relationship:

$$\frac{\alpha^2}{3} + \alpha\delta - \frac{\pi}{2\sqrt{2}} + \frac{\delta^2}{4} + w + s < \frac{1}{A}$$

where

α is a small angle variation from the constant radius path, see Fig. 4

δ is a small energy spread between ions from the source

A is the atomic weight of a particular element to be analyzed

w is width of entrance slit

s is width of exit slit

The above relationship assumes that a resolution of individual isotopes or mass units is desired; however, if such is not the case, the left-hand term of the equation may be made less than any other desired resolution. The approximate value of δ (energy spread) may be either calculated or observed and thus the maximum allowable α determined.

An investigation of the effects of magnetic field inhomogeneities results in the conclusion that the ion path must everywhere be at least a gap length away from the edges of the pole pieces. This however does not cause undue hardship as the lateral spread of the beam is maintained within close limits and thus the gap (distance between magnet pole pieces) may be quite small.

Inhomogeneities in the electric field pose a more difficult problem. It may be shown that

$$\frac{\text{accelerating voltage}}{\text{deflecting voltage}} = \frac{\rho}{2\delta}$$

thus the voltage ratio is a constant for the apparatus and with this ratio the condition for velocity focusing is satisfied for all mass, it remaining only to adjust the magnetic field to bring different masses to the focal point. However, the electric field set up between plates 17 and 18 is not uniform at the extremities of these plates in the vicinity of the source 11 and receiver 16. With these electric field irregularities it would be necessary to materially increase the width of the plates 17 and 18 in order for the ion beam not to be affected by the irregularities. Such an increase in plate width would necessitate a much larger magnet gap which is an undesirable requirement. However, the present invention circumvents this difficulty in another manner. A number of curved strip electrodes, such as 31 and 32, are placed between the plates 17 and 18. These strip electrodes are arranged along concentric circular arcs and are divided into two sets, one of which is on one side of the ion beam and the other on the opposite side of the beam, whereby pairs of electrodes of equal radius are disposed on opposite sides of the beam along the magnetic field. The two electrodes of each pair are electrically connected, and all of the pairs, as well as the plates 17 and 18, are connected to appropriate points on a voltage divider so as to achieve the desired distribution of the electric field in the region traversed by the ion beam. If V_1 is the voltage across the plates 17 and 18, and n the number of strips, the proper voltages to apply to potential dividers will be

$$\frac{1}{2n}V_1, \frac{3}{2n}V_1, \frac{5}{2n}V_1 \dots$$

starting with the divider nearest the low voltage plate 17.

With reference to the electrical circuit asso-

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ciated with the apparatus, Fig. 3 shows a power supply 41 applying a positive potential to the source anode 12, and equal negative potentials to the cathodes 13. In this particular embodiment the accelerating electrode 14 is grounded and a high positive accelerating potential applied to the anode 12 by a power supply 42. A deflecting voltage power supply 44 provides the potential to the deflecting plates 17 and 18 as well as to the strip electrodes. A potential divider 43 is connected across the deflecting voltage power supply 44, and the strip electrodes are connected at appropriate points on the divider so that the above prescribed potential relationship is maintained therebetween. Equal voltages of opposite sign are applied to the plates 17 and 18 which means that the midpoint between these plates should be at zero potential and thus the center pair of strip electrodes are grounded insuring a zero potential thereon.

As previously mentioned, various means may be employed to view the results, of which only one preferred embodiment is depicted herein. As shown, a saw-tooth generator 46 impresses a voltage of saw-tooth wave form upon the deflecting voltage. This potential variation on the deflecting plates causes the ion beam to sweep across the receiver. The receiver is connected to the vertical deflecting plates of a cathode ray oscilloscope and the saw-tooth voltage is impressed on the horizontal deflecting plates thus producing a trace of ion concentration vs. ion mass on the fluorescent screen of the oscilloscope.

A brief review of the operation of the apparatus shows that positive ions are formed at the source 11 and attracted from it by the relatively negative potential on the accelerating electrode 14. The magnetic field exerts a force on the ions at right angles to their direction of motion, thus forcing them to assume a semicircular orbit. The ions thus travel from the source 14 through the crescent-shaped region 23 to the receiver 16.

An electric field is maintained between the concentric circularly cylindrical plates 17 and 18 in such a direction as to urge the ions away from the center of their orbit. With the proper relationship maintained between the electric and magnetic fields, as given above, the effects of energy variations among the source ions is overcome and ions of like mass-to-charge ratios are focused at the receiver. There is also provided a number of pairs of strip electrodes, arranged as shown, which are attached to a voltage divider 43, thereby insuring the proper distribution of the electric field within the region of ion travel 23. Thus with a particular value of magnetic and electric fields all ions of a particular mass-to-charge ratio are focused at the receiver. A change in the value of the electric field causes ions of another mass-to-charge ratio to focus at the receiver.

A varying voltage, preferably of saw-tooth wave form, is impressed on the voltage divider 43 thus varying the electric field and sweeping the ion beam across the receiver, focusing ions of like mass-to-charge ratio in succession. As the receiver is connected to the vertical deflecting plates of a cathode ray oscilloscope and the saw-tooth voltage to the horizontal plates, a trace of ion magnitude vs. mass-to-charge ratio is obtained on the fluorescent screen of the oscilloscope. Calibration of the screen in accordance with the magnitude of the saw-tooth voltage makes it possible to immediately identify the elements

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and isotopes present in the source material and compare their relative abundance.

The foregoing presents a velocity-focused mass spectrometer in which a radial electric field is maintained perpendicular to the magnetic field and to the ion path. With this novel apparatus it is now possible for ions of differing initial velocity and direction to be precisely focused at a receiver. Further advantage lies in the utilization of "strip electrodes" whereby the problem of defocusing posed by the presence of the electric field is overcome. In addition to the advancements presented in the mass spectrometer proper, there is included a dependable, simply-operated means for determining the physical properties of the separated ions. The combination provides a novel and practical apparatus capable of identifying whatsoever ion, isotope, or element be desired.

Although this invention has been described with reference to a mass spectrometer, it will be obvious to one skilled in the art that ready adaptation to calutron use involves at most merely adjusting the potential impressed upon the voltage divider. Therefore, it is understood that no limitation is expressed or implied except as may be comprehended by the terms of the appended claims.

What is claimed is:

1. A mass separator comprising a source of ions, an ion current receiver, a beam of ions traversing an arcuate path therebetween and means including at least four curved electrodes parallel to and symmetrically disposed about said ion beam path for establishing a uniform, cylindrical electrical field for focusing ions emitted from said ion source at said ion receiver.

2. A mass separator comprising means establishing a magnetic field, a source of ions, an ion current receiver, a beam of ions traversing an arcuate path therebetween and means including a plurality of pairs of curved electrodes disposed parallel to said ion beam arc for establishing a radial electrical field influencing and perpendicular to the path of ions projected from said source through said magnetic field to said receiver, the two electrodes of each pair being disposed along a line parallel to the magnetic field and on opposite sides of the space through which the ions are projected.

3. A mass separator as claimed in claim 2 further characterized by means to apply a variable potential to said electrodes thereby varying the orbits of said ions, and further means providing a visual indication of the ion mass and relative abundance of each different mass.

4. A mass separator comprising a source of ions, an ion current receiver, and means for transmitting ions along curved paths from said source to said receiver, said means including two sets of curved electrodes parallel to said ion paths and disposed on opposite sides of said paths in planes substantially parallel to the planes of said paths for establishing an electric field substantially perpendicular to said paths.

5. A mass separator comprising a source of ions of different mass-to-charge ratios, an ion current receiver, velocity-focusing means including a plurality of electrostatic deflecting plates disposed on opposite sides of a region traversed by ions from said source to said receiver for focusing ions in a wide velocity range upon said receiver, a plurality of electrodes disposed between said plates, said plates and electrodes having substantially the same curvature as said ion paths and

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being maintained in substantially parallel relation thereto, a voltage divider including a plurality of resistors interconnecting said electrodes and plates for proportioning an applied voltage between them in a predetermined manner, and means including a variable voltage source connected across said voltage divider for successively focusing ions of different mass-to-charge ratios at said receiver.

6. A mass separator as claimed in claim 5 further characterized by means including a fluorescent screen whereby the relative abundance of each group of ions of like mass-to-charge ratios is visually represented.

7. In an electromagnetic mass separator including an ion source and means projecting a beam of ions therefrom, an ion receiver, and means establishing a magnetic field through the region between said source and receiver substantially perpendicular to said beam of ions, whereby said ions are constrained to travel an arcuate path; the improvement comprising a pair of curved electrostatic deflecting plates disposed parallel to said magnetic field on opposite sides of said ion beam and in substantially parallel relationship thereto, a plurality of pairs of curved

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electrodes substantially parallel to said ion beam path and disposed intermediate said plates with one of the electrodes of each pair lying in the magnetic projection of the other, potential supply means connected across said plates and electrodes for establishing a radial electrostatic field through the region traversed by said ion beam, whereby ions are focused at said receiver substantially independent of their initial velocity.

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