METHOD OF SEPARATING IONS OF DIFFERENT SPECIFIC CHARGES

Filed Dec. 24, 1958 3 Sheets-Sheet 1

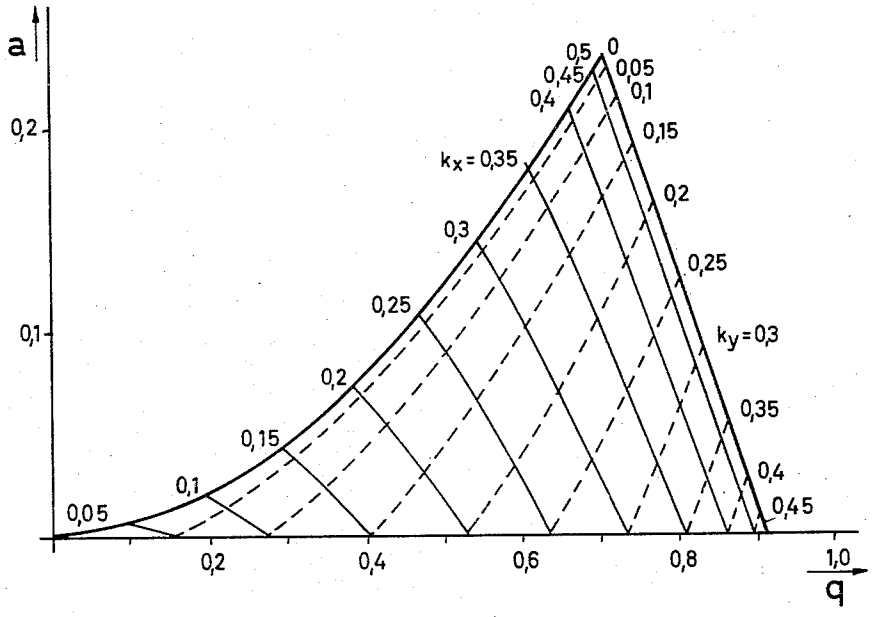

Fig. 1

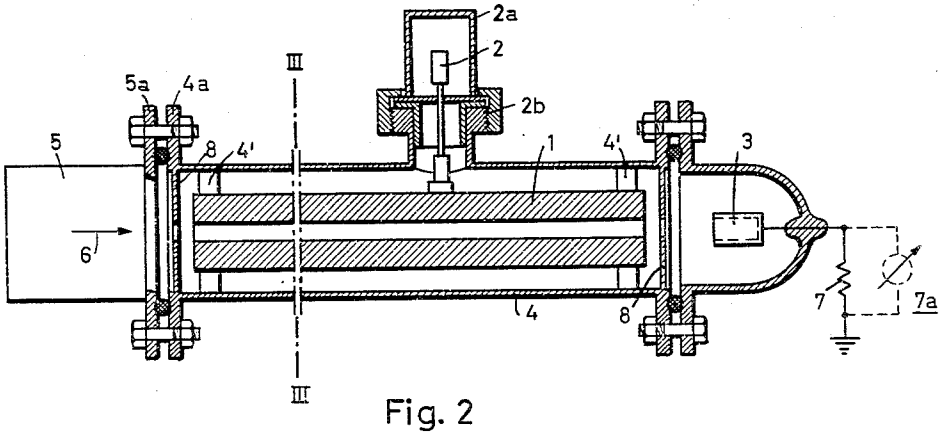

Fig. 2

METHOD OF SEPARATING IONS OF DIFFERENT SPECIFIC CHARGES

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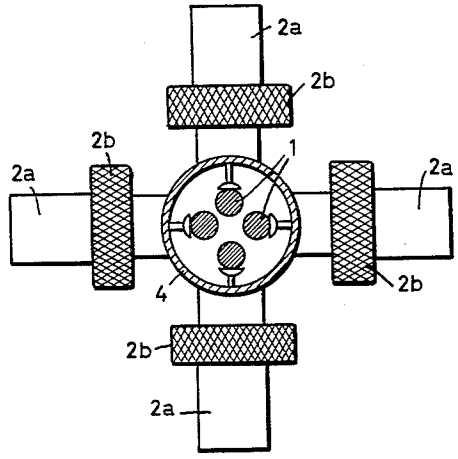

Fig. 3

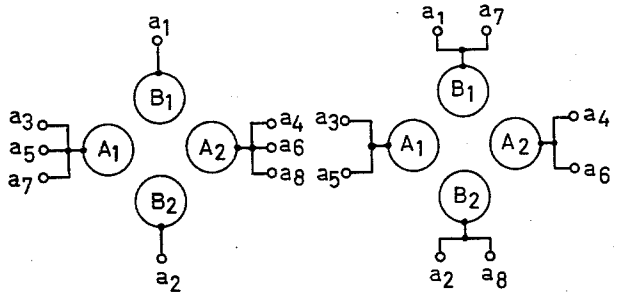

Fig. 4

Fig. 5

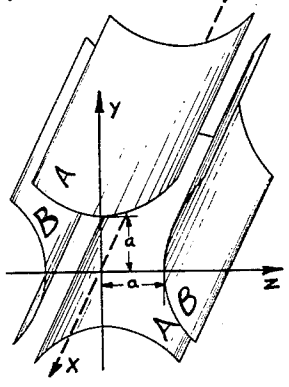

Fig. 7

METHOD OF SEPARATING IONS OF DIFFERENT SPECIFIC CHARGES

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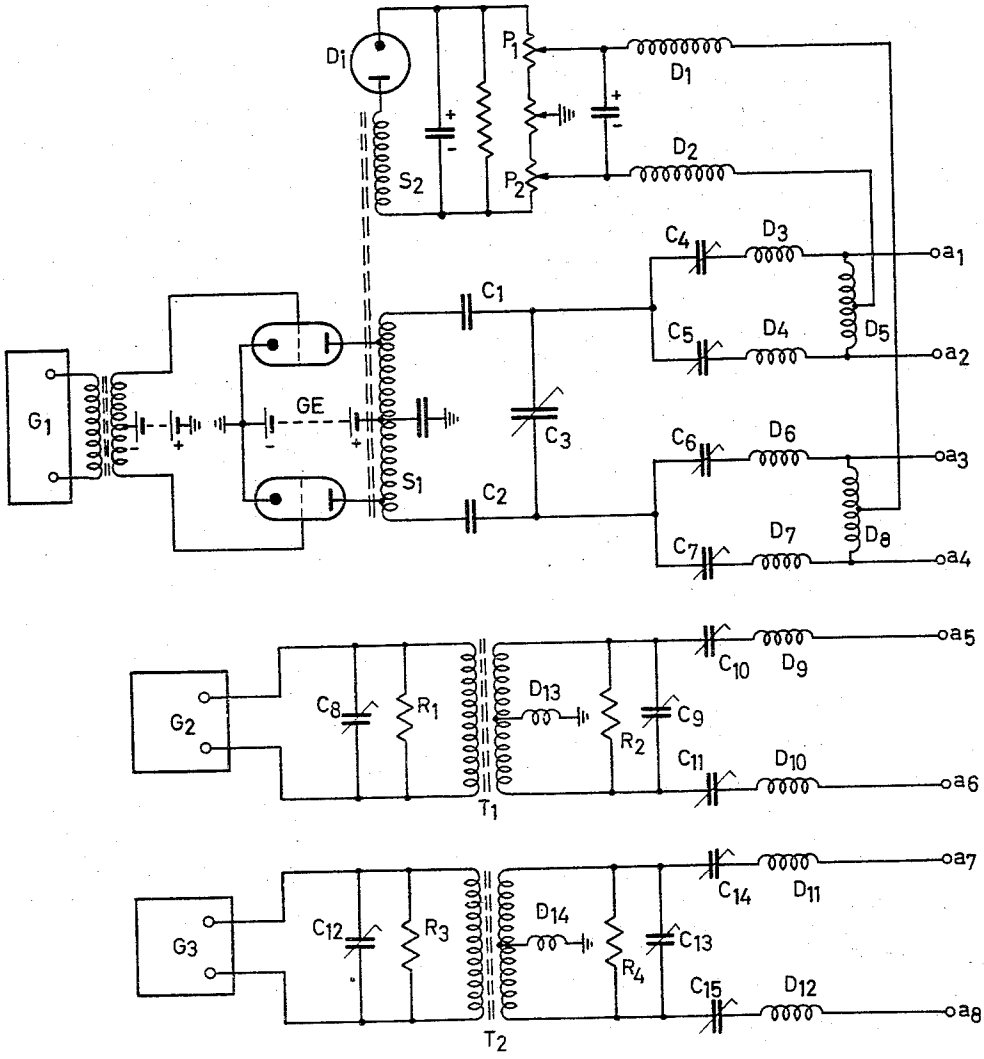

Fig. 6

United States Patent Office 2,950,389 Patented Aug. 23, 1960

2,950,389

METHOD OF SEPARATING IONS OF DIFFERENT SPECIFIC CHARGES

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Filed Dec. 24, 1958, Ser. No. 782,838

12 Claims. (Cl. 250—41.9)

Our invention relates to a mass-spectrometer method for the separation or separate indication of ions of respectively different specific electric charges and, more particularly, to a method based upon the principle known from the German Patent No. 944,900 and disclosed in U.S. application Serial No. 476,812 filed December 21, 1954. According to that principle the ions are shot into a periodically varying electric field whose potential φ is a square function of the coordinates x, y, z of the general form

$$\varphi=f(t)\cdot(\alpha x^2+\beta y^2-\gamma z^2)$$

wherein $f(t)$ denotes any chosen periodic function of time (t), and α, β, γ are positive constants which satisfy the equation of $\alpha+\beta=\gamma$ but are otherwise selectable at will.

The ions, shot from an ion source into the periodically varying electric field, are excited by the field to perform oscillations while traveling along trajectories which are either stable or instable depending upon the specific electric charges of the respective ions. It will be evident from page 1 of the German patent that specific charge means

$$\frac{e}{m}$$

where e is the electric charge and m the mass of the particles. The ions that follow a stable trajectory pass through the electric field onto a collector electrode or other target, whereas the ions following instable trajectories impinge upon the laterally located electrodes that produce the electric field, thus being prevented from reaching the target. In this manner the desired isotope separation or separate indication is obtained.

The above-mentioned periodic function $f(t)$ may be constituted, for example, by a sinusoidal oscillation superimposed upon a constant finite value. Suitably shaped electrodes serve for producing the electric field of the above-mentioned periodic potential. In the special case of the sinusoidal field potential just mentioned, the electrodes are impressed by a constant direct voltage and also by a sinusoidal voltage of high frequency. As a result, there result stable ranges in which the oscillation amplitude of ions of a given specific electric charge does not exceed a given maximum value. Hence, only such ions can pass from the ion source between the electrodes to the target. The other ions, having different specific electric charges and performing instable oscillations after entering the periodic electric field, assume oscillation amplitudes of such large magnitude as to impinge upon the electrodes. For further explanation of these phenomena, reference may be had to the above-mentioned German patent. As also disclosed in the patent, a narrow instable range can be embedded in a wide stable range by superimposing upon a rotationally symmetrical high-frequency field another alternating field of smaller amplitude or potential whose frequency is one-half of that of the high-frequency field. This is supposed to afford

a separation of ions of a given charge out of an isotope mixture.

However, when using a superimposed alternating field of one-half of the frequency of the high-frequency main field, the desired results can be attained only for a very limited number of practical applications.

It is therefore an object of our invention to devise a method of isotope separation which, based upon the principle above mentioned, is more generally applicable and can be used more reliably with rotationally symmetrical as well as non-rotationally symmetrical electric fields.

Another object of the invention is to provide a method and means capable of simultaneously separating two or more isotopes, i.e. ions of respectively different specific charges, from an isotope mixture comprising more than the two isotopes to be separated.

Still another object is to devise a method and means for converting an isotope mixture of a given composition to a desired different composition with respect to the relative proportions of the differently charged ions.

In accordance with our invention, we pass a flow of differently charged ions through a periodic high-frequency field substantially as known, but superimpose upon that field another alternating field whose frequency is adjusted to the selected working point within the stable range. More specifically, the superimposed additional alternating field is given a frequency which coincides at least approximately with the fundamental or upper harmonic oscillation of ions having a predetermined specific charge, thus enforcing instable paths for these particular ions.

The fundamental oscillation frequency of ions of a given specific electric charge, traveling through an electric field comprised of a constant unidirectional component and a periodically variable high-frequency component, depends not only upon said electric charge of the ions but also upon the magnitude of the field-producing direct voltage, the amplitude of the field-producing high-frequency voltage, the magnitude of the high-frequency itself, and also upon the geometry of the field-producing electrodes. Since these data are known for any given device, the fundamental oscillation frequency of the ions of a given charge can readily be determined for any given working point. This fundamental frequency is proportional to the high frequency, the proportionality factor k being determined by the chosen working point within the stable range. The upper harmonics in each case are the direct result of the sum or difference of integral multiples of the high field frequency on the one hand, and the fundamental oscillation frequency of the ions on the other hand.

The invention will be further described with reference to the drawings in which:

Fig. 1 is an explanatory graph relating to the method as performed by means of apparatus as shown in Figs. 2 and 3;

Fig. 2 is a longitudinal and sectional view of an apparatus for isotope separation according to the invention;

Fig. 3 is a cross section of the apparatus along the line III—III in Fig. 2;

Figs. 4 and 5 are explanatory and show two different ways of applying the necessary field voltages to the electrodes of the apparatus; and

Fig. 6 is an electric circuit diagram of the components for producing the field voltages.

Fig. 7 illustrates one form of elongated electrodes of the hyperbolic type.

The graph shown in Fig. 1 is a so-called stability diagram for a cylinder-symmetrical electrode arrangement whose symmetry axis constitutes the z axis. The magnitudes a and q represented by the coordinate axes of

the diagram determine the working point and result from the data of the device as follows:

$$a=4\frac{e}{m}\frac{U}{r^2\omega^2} \qquad q=2\frac{e}{m}\frac{V}{r^2\omega^2}$$

The terms used in these equations denote the following:

e charge
m mass
U direct voltage
V high-frequency amplitude
r spacing between electrodes

$\frac{\omega}{2\pi}$ high frequency

The stability range is indicated in the diagram by a heavy line. Shown within the range so indicated are marker lines for the proportionality factors k. The full marker lines apply to the x component, and the broken marker lines to the y component of the ion trajectory. The fundamental and upper harmonics are different for the two components, which must be taken into consideration when performing the method according to the invention.

The above-described method of the invention can be modified for separating ions of several given, different electric charges from a more comprehensive mixture of isotopes. For this purpose, a plurality of additional alternating fields of correspondingly different frequencies are simultaneously superimposed upon the combined constant unidirectional and high-frequency fields.

It has been found that the tuning of the frequency of the superimposed field to the fundamental or upper harmonic frequencies of the ions need not be strict. In the event of frequency differences, the traveling ions oscillate along their trajectory at beat frequencies with amplitudes that may become so large as to result in the desired separation.

According to another feature of our invention, advantage is taken of this phenomenon for simultaneously separating ions of respectively different specific charges, without the need for using as many superimposed frequencies as there are different electric charges. Accordingly, the separation is effected by superimposing one or more alternating fields whose frequencies, at least with respect to some of these fields, are between the fundamental or upper-harmonic oscillation frequencies of the differently charged ions to be separated.

The ranges of the respectively different electric charges of the isotopes to be separated need not be contiguous. For example, ions of a given specific charge can be separated by superimposing an alternating field whose frequency corresponds to an upper harmonic of these ions, whereas ions of a different charge are simultaneously separated by means of a superimposed frequency corresponding to the fundamental frequency of the latter ions, as long as these different oscillation frequencies are relatively close to each other. In such cases, it is also possible to utilize the fact that the oscillation frequencies for the individual components (y, x) are different. The fundamental and upper harmonic frequencies of the ions not to be separated must be sufficiently remote from the frequency of the superimposed alternating field.

By selecting the frequencies and/or the amplitudes of the superimposed alternating fields, the beat-frequency amplitudes for the ions of the respectively different electric charges can be separately determined. The higher the amplitude of the superimposed fields is chosen, the broader will be the range in which the separation takes place in each case. This offers the possibility to convert a given isotope mixture by means of a single operating process to a desired different composition. In this case, individual quantities of ions can be fully separated from the mixture, or all components of the mixture are varied only with respect to their relative proportions. This possibility of simply and rapidly changing the composition of a mixture of isotopes represents a particular advantage of the method according to the invention.

The above-mentioned features of the invention will be more fully understood from the following description of the apparatus shown in Figs. 2 to 6 and from the numerical examples given further below.

The apparatus illustrated in Figs. 2 and 3 comprises an evacuable vessel **4** in which four cylindrical rod-shaped electrodes **1** are symmetrically mounted in parallel relation to each other. Each two electrodes, located diametrically opposite each other, are mutually spaced a distance equal to the electrode diameter. Instead of giving each electrode a strictly circular cross section, it may also be given a hyperbolic surface at least at the side facing the other electrodes, as shown in said German Patent No. 944,900, issued June 28, 1956. The electrodes are kept in proper position relative to each other and to the vessel by means of insulating discs **4'** of ceramic material and are preferably adjustable.

The direct and alternating voltages required for producing the electric field between the electrodes are supplied thereto by conductors **2** which are located in housings **2***a* vacuum-tightly connected with the vessel **4** by means of screw caps **2***b*. A conventional ion source **5**, comprising a shock-ion generator or a low-voltage arc discharge, is joined and hermetically sealed with the vessel **4** by means of flanges **4***a*, **5***a*. From source **5**, the ions are shot in the direction of the arrow **6** into, and axially along, the field space between the electrodes with a given kinetic energy. The ions having a stable trajectory pass through the entire axial length of the electric field and reach the collector electrode **3** which is grounded through an external resistor **7** by a lead vacuum-tightly passing through the container wall. The voltage drop of resistor **7** due to the discharge from electrode **7** to ground can be measured, for example by means of a voltmetric device **7***a*. Located at both axial ends of vessel **4** are circular diaphragms **8** which have respective center openings for the passage of the ions and which shield the ion source and the collector electrode **3** from the high-frequency field between the electrodes **1**. As mentioned above, those ions that are excited by the high frequency field to oscillate along their trajectory with unlimited amplitude, cannot reach the collector electrode **3** but impinge upon the electrodes **1**.

The direct voltages and alternating voltages for producing the field are supplied to the electrodes from the generating components illustrated in Fig. 6 in accordance with one of the diagrams shown in Figs. 4 and 5. For better distinction, the electrodes denoted by **1** in Figs. 2 and 3 are designated in Figs. 4 and 5 by A_1, A_2, B_1 and B_2. Impressed upon these four electrodes are the voltages mentioned in the foregoing general description of the method according to the invention and more fully specified hereinafter. Supplied to each electrode is a direct voltage as well as a superimposed alternating voltage of high frequency for producing the main guiding field. As schematically shown in Fig. 4, the electrodes A_1 and A_2 are further supplied with one or two additional superimposed alternating voltages. However, the supply of the alternating voltages may also be such that a first additional alternating voltage is applied to the electrodes A_1 and A_2, and a second alternating voltage to the electrodes B_1 and B_2 as is shown in Fig. 5. The terminals a_1 to a_8 according to Fig. 4 or Fig. 5 are conductively connected with the correspondingly designated terminals respectively of the circuit diagram according to Fig. 6.

According to Fig. 6, a high-frequency generator G_1 for the main guiding field acts through a transformer coupling and a push-pull final stage GE upon an inductance coil S_1. The coil S_1 forms together with capacitors C_1, C_2, C_3 and the capacitance of the electrodes relative to each other (B_1 and B_2 relative to A_1 and A_2) a resonance circuit tuned to the frequency of the generator

G_1. Two tank circuits formed of capacitors C_4, C_5 and inductance coils D_3, D_4, D_5 on the one hand, and capacitors C_6, C_7 and coils D_6, D_7, D_8 on the other hand, both being likewise tuned to the frequency of the high-frequency generator G_1, form a short circuit for the electrode pairs A_1, A_2 and B_1, B_2 with respect to the high frequency of the main guiding field. Inductively coupled with the inductance coil S_1 is another inductance coil S_2 whose alternating voltage is rectified by a diode D*i*. The filtered direct voltage is adjustable by means of potentiometer resistors P_1 and P_2 and thus can be placed into different fixed relations to the amplitude of the high-frequency voltage of the main guiding field. The direct voltage is connected to terminals a_1 to a_4 through blocking reactors D_1, D_8 and D_2, D_5. With an electrode connection according to Fig. 4, the electrodes A_1 and A_2 are connected to one pole of the direct voltage, and the electrodes B_1 and B_2 are connected to the other pole.

A second frequency generator G_2 for a first resonance field acts upon a resonance transformer T_1 which forms a tank circuit together with capacitors C_8, C_9 and together with the mutual capacitance of two opposite electrodes. This tank circuit is tuned to the frequency of the generator G_2. Connected in parallel to capacitors C_8 and C_9 are terminal and damping resistors R_1 and R_2. The resonant connecting circuit formed by capacitors C_{10} and C_{11} with inductance coils D_9 and D_{10} is likewise tuned to the frequency of the generator G_2 and acts together with a grounded reactor D_{13} to block the voltage of the main guiding field relative to ground.

In the two connecting possibilities according to Figs. 4 and 5, the electrodes A_1 and A_2 are connected to the terminals a_3, a_5, and a_4, a_6 respectively.

The above-mentioned reactors D_6 to D_8 and the capacitors C_6 and C_7 in the circuit of the high-frequency generator G_1 serve to prevent the voltage of the superimposed first resonance field from being short circuited.

Another frequency generator G_3 is provided for producing a second resonance field. The generator G_3 supplies its voltage to the terminals a_7 and a_8 by a circuit connection corresponding in design and operation to that described above with reference to generator G_2. The operation of the network connection for generator G_3 is also identical with that described above for generator G_2, the resonance circuits C_{14}, D_{11} and C_{15}, D_{12} being tuned to the frequency of generator G_3.

The generator G_3 need not in all cases be connected to the electrodes. On the other hand, additional frequency generators (not illustrated) may be connected with the electrodes by circuit connections analogous to those described above.

Fig. 7 illustrates the hyperbolic type of elongated electrodes mentioned above, and described in said German patent. The opposite pairs are designated A, A and B, B respectively.

In summary, it will be recognized that the electrodes are impressed with component direct voltage (from D*i*) and component high-frequency voltage (from G_1) for producing the main guiding field, and that one or more resonance fields of predetermined, respectively different frequencies are superimposed by means of one or more additional generators (G_2, G_3). With reference to Figs. 4 and 5, the illustrated terminals a_1 to a_8 may either all be connected to the frequency generators according to Fig. 6 or, instead, the terminals a_5 and a_6 and the terminals a_7 and a_8 may not be conductively connected with the corresponding frequency generators. In case all terminals a_1 to a_8 are to be active, the connection according to Fig. 5 is preferable, as a rule, if the frequencies of both resonance fields are very close to each other.

It will be recognized that the above-described apparatus according to Figs. 2 to 6 is also suitable for permitting a selection of the frequencies or a selection of the amplitudes of the additionally superimposed alternating fields, without necessitating any change in the illustrated devices. The adaptation to the particular selected frequencies is effected merely by correspondingly changing the tuning of the resonant connecting circuits, this being apparent from the provision of variable capacitances such as those denoted by C_3, C_4, C_5.

The method performed by the operation of the apparatus will be further explained presently.

In a system of rectangular coordinates x, y, z, the motion of a single-charge corpuscle (ion) which is subjected to a variable voltage

$$\varphi 0 = U + V\cos\omega t \tag{1}$$

can be represented by the following equations for the three individual components of motion:

$$m\ddot{x} + e(U + V\cos\omega t)\frac{x}{r^2} = 0 \tag{2}$$

$$m\ddot{y} - e(U + V\cos\omega t)\frac{y}{r^2} = 0 \tag{3}$$

$$m\ddot{z} = 0 \tag{4}$$

The terms used in these equations have the following meaning:

U = direct-voltage component

$V\cdot\cos\omega t$ = a superimposed alternating voltage

$m = M\cdot m_H$ = atomic weight of the particular substance, which is equal to the product of the mass number M times the atomic weight m_H of hydrogen;

e = electric charge of a single-charge corpuscle, amounting to $4.8\cdot10^{-10}$ electrostatic charge units;

$\frac{\omega}{2\pi}$ = frequency of the alternating voltage

V = amplitude of the alternating voltage

r = one-half of the distance between two mutually opposite, cylindrical electrodes each having the radius r.

If one sets:

$$4\frac{e}{m}\cdot\frac{U}{r^2\omega^2} = a \tag{5}$$

$$2\frac{e}{m}\cdot\frac{V}{r^2\omega^2} = q \tag{6}$$

$$\omega t = 2s \tag{7}$$

$$x'' = \frac{d^2x}{ds^2} \tag{8}$$

$$y'' = \frac{d^2y}{ds^2} \tag{9}$$

the equations (2) and (3) convert to the normal form of Mathieu's differential equations:

$$x'' + [a - 2q\cos(2s+\pi)]x = 0 \tag{10}$$

$$y'' - [a + 2q\cos 2s]\cdot y = 0 \tag{11}$$

Consequently the solutions, for example of Equation 10, have within the stable range the form

$$x = A\sum_{n=-\infty}^{+\infty} c_{2n}\cdot\cos\left(n+\frac{\beta}{2}\right)\omega t + B\sum_{n=-\infty}^{+\infty} c_{2n}\sin\left(n+\frac{\beta}{2}\right)\omega t \tag{12}$$

The starting conditions (radiation diameter and aperture angle of the enclosed ion beam) and the maximum oscillation amplitudes determined by these conditions, are given by the magnitudes of the constants A and B. The starting conditions must be so chosen that the finite maximum amplitude of oscillation remains smaller than the electrode spacing $2r$ because otherwise ions with stable trajectories will also be separated.

The coefficients c_{2n} and β depend only upon the field magnitudes and hence upon a and q. Ions of the same mass number differ, at a given point under observation,

only with respect to the constants A and B. That is, such ions oscillate with different amplitudes but do not exhibit differences with respect to their respective frequency spectrums or their fundametal frequencies. The fundamental frequencies are dependent only upon a and q.

With a given available power of the device, the following values apply for example to the separation of a single-charge medium having the mass number $M=200$:

$e=4.8\cdot10^{-10}$ (electrostatic charge units)
$a=0.112$
$q=0.66$
$r=1.5$ cm.

$f=\frac{\omega}{2\pi}=1.5$ megacycles per sec.

$V=14$ kv.

$U=\frac{1}{2}\cdot V\frac{a}{q}=7\cdot0.17=1.19$ kv.

When using the above-mentioned specific values in a device as described above with reference to Figs. 2 to 6, the values a and q are located in the middle of the stability diagram of Fig. 1; and the value

$$\frac{a}{q}=0.17$$

represents a straight line which starts from the zero point and intersects the diagram in two points. These two points have the coordinates $a_1=0.055$, $q_1=0.335$, and $a_2=0.138$, $q_2=0.795$.

The masses m_1 and m_2 can be calculated from Equations 5 and 6 by using the above-given values for U, r, ω, and e. It results that $m_{1,2}=1.67\cdot10^{-24}\cdot M_{1,2}$.

All masses between these two are stable and travel from the ion source through the interspace between the electrodes onto the collector electrode. Now, if the mass of mass number $M=200$, located within the mentioned range of masses, is to be separated, then one electrode pair must be caused to produce a resonance alternating field with a resonance frequency corresponding to the oscillation frequency of this particular mass. As a result, the ions of the mass $M=200$ are gradually excited by resonance to oscillate with such a large amplitude that they reach the field electrodes and thus are eliminated from the ion beam. The resonance frequency can be determined from the solutions of the above-mentioned Mathieu's differential equations. The natural frequency of the ion in the guiding field of the frequency ω amounts to

$$\omega_0=\left(n\pm\frac{\beta}{2}\right)\omega$$

and can be determined for the fundamental oscillation ($n=0$) as

$$\omega_0=\frac{\beta}{2}\omega$$

It follows that the frequency of the fundamental oscillation of the ion along its trajectory is:

$$f_0=\frac{\beta}{2}f$$

The value

$$\frac{\beta}{2}$$

is entered in Fig. 1 for the x and y directions with the designation k_x and k_y, the z-direction extending along the longitudinal symmetry axis of the electrode assembly. For occurrence of resonance in the x-direction of an ion having the mass number $M=200$, the intersection between a and q applying to this particular mass can be determined by interpolation, and one thus obtains the value $k_x=0.327$.

The necessary resonance frequency is

$$f_0=k_x\cdot f=0.327\cdot1.5=0.49 \text{ Mc.p.s.}$$

The amplitude V_0 of the resonance frequency may be chosen to be approximately 2% of the voltage V. This corresponds, in the example here being discussed, to $V_0=280$ volts. The percentage just given has been determined by experiments. When larger amplitudes are chosen, too many neighboring masses are separated together with the one of primary interest.

To perform the separation with the aid of the desired economical amount of power N, the best suitable values can be determined by tests. The power N can be determined from the semi-empiric equation

$$N=6\cdot10^{25}\cdot C\cdot M^2\cdot r^4\cdot f^5/\theta \tag{13}$$

wherein C denotes the capacitance of the electrodes in [F] (Farad), and θ denotes the resonance quality.

With a length $L=600$ cm. of the electrodes and an electrode diameter of $r=1.5$ cm., the value for C can be determined from the Equation 13 as $C=9\cdot10^{-10}[F]$. By selecting $\theta=200$, one obtains $N=4.2$ kw.

The ions issuing from the ion source are subjected to a given accelerating voltage U_E (between ion source and grounded collector) which imparts to the ions the necessary and correct velocity at their entrance into the electrode range.

The semi-empirical equation for the accelerating voltage U_E is

$$U_E=\frac{2\cdot f_s\cdot l^2\cdot m\cdot300}{e} \text{ volts} \tag{14}$$

with the beat frequency

$$f_s=\frac{\beta\cdot f\cdot\Delta M}{2M}$$

and $\Delta M=M_n-M_{n\pm m}$ with $n=1\ldots n$ and $m=1\ldots m$

$\Delta M=1$ for neighboring masses.

It follows for the specific example ($M=200$) here under consideration that the necessary plate voltage of the device is $U_E=900$ volts.

The permissible current flow from the ion source through the electrode gap follows from Gauss' theorem concerning the field strength produced by the space charge. The formula for the permissible current is

$$I_E=4.9\cdot10^{-5}\cdot r\cdot V\cdot\sqrt{\frac{U_E}{M}} \text{ milliamps} \tag{15}$$

wherein r is given in cm., V in volt, and U_E in volt. Equation 15 is based upon a constant space-charge density, resulting in a maximal space-charge field strength of

$$E_{max}=4.25\cdot10^{-2}\frac{V}{r}$$

The separation of adjacent masses (adjacent isotopes) effected in this manner is approximately 50%.

The foregoing explanations relating to the fundamental oscillations of the ions along their trajectory apply also for upper harmonics, it being only necessary to determine the particular resonance frequency from

$$\omega_0=\left(n\pm\frac{\beta}{2}\right)\omega \tag{16}$$

by introducing the order numbers $n=1, 2\ldots$ correlated to the individual upper harmonic oscillations.

All above-presented equations apply to the motion of a single-charge ion in a hyperbolic four-pole field as is realized, strictly or in sufficient approximation, by the device illustrated in Figs. 2, 3 and described above.

We claim:

1. The method of separating ions of respectively different specific electric charges, which comprises passing the ions through an electric field having a field potential (φ) periodically varying in accordance with a square function of the space coordinates (x, y, z), said function having the form

$$\varphi=f(t)\cdot(\alpha x^2+\beta y^2-\gamma z^2)$$

wherein $f(t)$ is a periodic function of time and α, β, γ are positive constants satisfying the equation $\alpha+\beta=\gamma$; and superimposing upon said field another alternating field whose frequency coincides approximately with an oscillation frequency of ions of pre-selected specific charge, whereby said ions of selected charge are forced to travel on instable trajectory paths.

2. The method of separating ions of respectively different specific electric charge, which comprises passing the ions through an electric field formed between mutually spaced electrodes and having a constant component and a high-frequency component, said field having a potential (φ) of the general form

$$\varphi=f(t)\cdot(\alpha x^2+\beta y^2-\gamma z^2)$$

wherein $f(t)$ is a periodic function of time, and x, y, z are space coordinates, and α, β, γ are positive constants satisfying the equation $\alpha+\beta=\gamma$; and superimposing upon said field an alternating field of lower frequency than said high-frequency component, said superimposed frequency coinciding approximately with an oscillation frequency of ions of pre-selected specific charge, whereby said ions of selected charge are forced to travel on instable trajectory paths.

3. In the method according to claim 2, said frequency of said superimposed alternating field being approximately coincident with the fundamental oscillation frequency of said ions of pre-selected specific charge.

4. In the method according to claim 2, said frequency of said superimposed alternating field being approximately coincident with an upper harmonic oscillation frequency of said ions of pre-selected specific charge.

5. The method of separating ions of respectively different specific electric charges from an isotope mixture, which comprises passing the ions through an electric high-frequency field having a potential (φ) of the form

$$\varphi=f(t)\cdot(\alpha x^2+\beta y^2-\gamma z^2)$$

wherein $f(t)$ is a periodic function of time, and x, y, z are space coordinates, and α, β, γ are positive constants meeting the equation $\alpha+\beta=\gamma$; and superimposing upon said high-frequency field a plurality of alternating fields of respectively different frequencies corresponding approximately to the oscillation frequencies of ions of predetermined different specific charges respectively, whereby said latter ions are simultaneously separated from the isotope mixture.

6. In the method according to claim 5, said superimposed alternating fields comprising at least one field having a frequency between the fundamental oscillation frequency of the ions of one given specific charge and an upper harmonic frequency of the ions having another given specific charge.

7. In the method according to claim 5, said superimposed alternating fields having predetermined different amplitudes respectively for obtaining respectively different degrees of separation for said ions of respectively different predetermined specific charges.

8. An apparatus for separating ions of respectively different specific electric charges by causing the ions to assume oscillations having amplitudes correlative with the specific charges, comprising a vacuum vessel, an ion source and a collector electrode axially spaced from each other in said vessel, two pairs of elongated field electrodes extending in said vessel between said source and said collector electrode, said electrodes presenting substantially cylindrically curved surfaces in symmetrical and radially spaced relation to the common axis thereof, the spacing apart of said surfaces being predetermined so that ions having the larger oscillation amplitudes impinge on said electrodes, a source of component direct voltage and a source of component high-frequency voltage jointly connected to said field electrodes to provide a resultant main guiding field between said pairs of electrodes, and circuit means providing a source of alternating voltage of a lower frequency connected to at least one of said electrode pairs, and means for tuning the frequency of the latter voltage to resonance with the oscillations imparted by said main guiding field to an ion of a selected specific electric charge so as to augment the tendency of said ion to impinge upon said field electrodes.

9. Apparatus for separating ions of respectively different specific electric charges by causing the ions to assume oscillations having amplitudes correlative with the specific charges, comprising a vacuum vessel, an ion source and a collector electrode axially spaced from each other in said vessel, two pairs of elongated field electrodes extending in said vessel between said source and said collector electrode, said electrodes presenting substantially cylindrically curved surfaces in radially spaced relation to the common axis thereof, the spacing apart of said surfaces being predetermined so that ions having the larger oscillation amplitudes impinge on said electrodes, a source of component direct voltage and a source of component high-frequency voltage jointly connected to said field electrodes to provide a resultant main guiding field between said pairs of electrodes, and a plurality of alternating voltage sources connected to at least one of said electrode pairs and having different frequencies, lower than that of said high-frequency component, and means for tuning the latter frequencies to resonance with the oscillations imparted by said main guiding field to ions of selected and respectively different specific electric charges so as to augment the tendency of said ions to impinge upon said elongated electrodes.

10. An apparatus for separating ions of respectively different specific electric charges by causing the ions to assume oscillations having amplitudes correlative with the specific charges, comprising a vacuum vessel, an ion source and a collector electrode axially spaced from each other in said vessel, two pairs of elongated field electrodes extending in said vessel between said source and said collector electrode in symmetrical and radially spaced relation to the common axis thereof, said electrodes being substantially hyperboloid in transverse section, the spacing apart of the hyperboloid surfaces being predetermined so that ions having the larger oscillation amplitudes impinge on said electrodes, a source of component direct voltage and a source of component high-frequency voltage jointly connected to said field electrodes to provide a resultant main guiding field between said pairs of electrodes, and circuit means providing a source of alternating voltage of lower frequency connected to at least one of said electrode pairs and means for tuning the frequency of the latter voltage to resonance with the oscillations imparted by said main guiding field to an ion of a selected specific electric charge so as to augment the tendency of said ion to impinge upon said field electrodes.

11. Apparatus for separating ions of respectively different specific electric charges by causing the ions to assume oscillations having amplitudes correlative with the specific charges, comprising a vacuum vessel, an ion source and a collector electrode axially spaced from each other in said vessel, two pairs of elongated field electrodes extending in said vessel between said source and said collector electrode in symmetrical and radially spaced relation to the common axis thereof, said electrodes being substantially hyperboloid in transverse section, the spacing apart of the hyperboloidal surfaces being predetermined so that ions having the larger oscillation amplitudes impinge on said electrodes, a source of component direct voltage and a source of component high-frequency voltage jointly connected to said field electrodes to provide a resultant main guiding field between said pairs of electrodes, and a plurality of alternating voltage sources connected to at least one of said electrode pairs and having different frequencies which are

lower than said high-frequency component, and means for tuning the latter frequencies to resonance with the oscillations imparted by said main guiding field to ions of selected and respectively different specific electric charges so as to augment the tendency of said ions to impinge upon said elongated electrodes.

12. An apparatus for separating ions of respectively different specific electric charges by causing the ions to assume oscillations having amplitudes correlative with the specific charges, comprising a vacuum vessel, an ion source and a collector electrode axially spaced from each other in said vessel, two pairs of elongated field electrodes extending in said vessel between said source and said collector electrode in symmetrical and radially spaced relation to the common axis thereof, the spacing apart of said surfaces being predetermined so that ions having the larger oscillation amplitudes impinge on said electrodes, a source of component direct voltage and a source of component high-frequency voltage jointly connected to said field electrodes to provide a resultant main guiding field between said pairs of electrodes to

produce an electric field having a field potential (φ) periodically varying in accordance with a square function of the space coordinates (x, y, z), said function having the form

$$\varphi=f(t)\cdot(\alpha x^2+\beta y^2-\gamma z^2)$$

wherein $f(t)$ is a periodic function of time and α, β, γ are positive constants satisfying the equation $\alpha+\beta=\gamma$; and circuit means providing a source of alternating voltage of a lower frequency connected to at least one of said electrode pairs, and means for tuning the frequency of the latter voltage to resonance with the oscillations imparted by said main guiding field to an ion of a selected specific electric charge so as to augment the tendency of said ion to impinge upon said field electrodes.

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UNITED STATES PATENT OFFICE

CERTIFICATION OF CORRECTION

Patent No. 2,950,389 August 23, 1960

Wolfgang Paul et al.

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

In the heading to the printed specification, between lines 9 and 10, insert -- Claims priority, application Germany December 27, 1957 --.

Signed and sealed this 25th day of April 1961.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents