June 23, 1964 K. L. BROWN ETAL 3,138,706

METHOD OF FOCUSING CHARGED PARTICLES TO PROVIDE ZERO MOMENTUM DISPERSION

Filed April 28, 1961

Fig-1

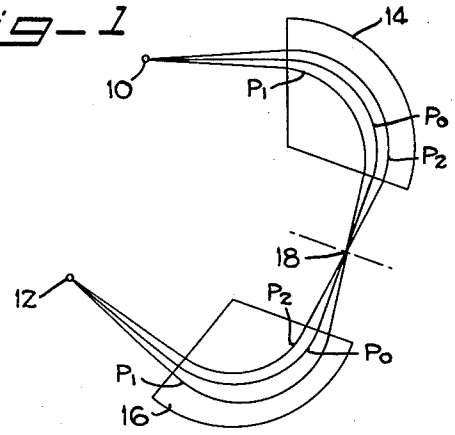


Fig-2

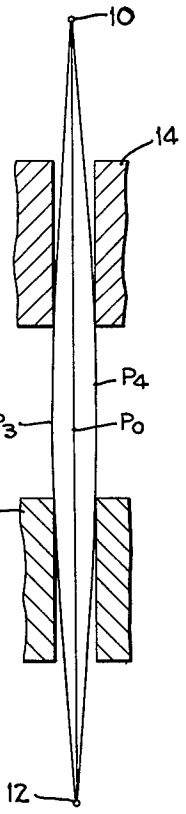


Fig-3

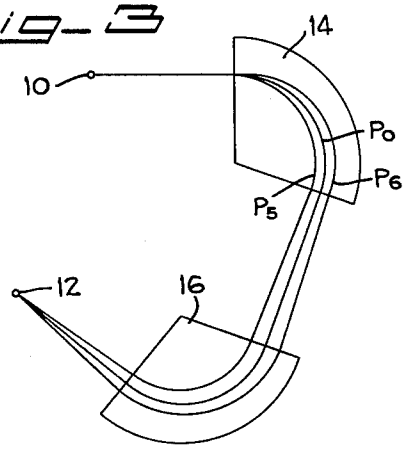


Fig-4

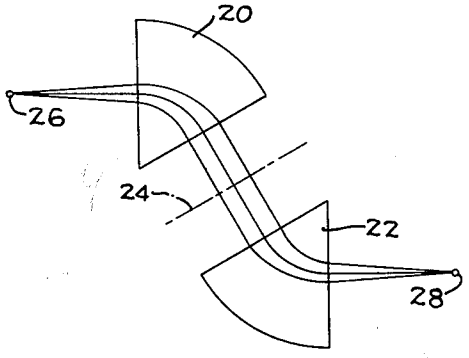
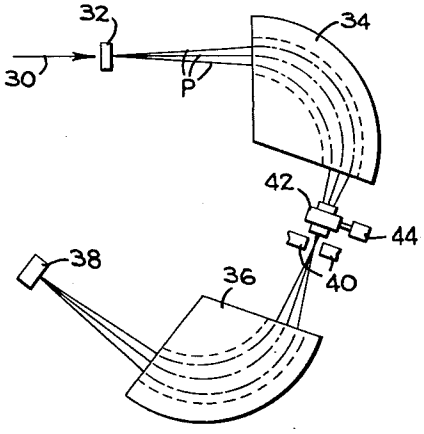


Fig-5



INVENTORS.
KARL L. BROWN
WOLFGANG K. H. PANOFSKY
BY JOHN F. STREIB

Paul B. Eilis

PATENT AGENT

United States Patent Office 3,138,706
Patented June 23, 1964

3,138,706
METHOD OF FOCUSING CHARGED PARTICLES TO PROVIDE ZERO MOMENTUM DISPERSION

Karl L. Brown, 1990 Santa Cruz St., Menlo Park, Calif., and Wolfgang K. H. Panofsky, Los Altos, Calif., and John F. Streib, Seattle, Wash.; said Panofsky and said Streib assignors to said Brown

Filed Apr. 28, 1961, Ser. No. 106,331
5 Claims. (Cl. 250—41.9)

The present invention relates to the focusing and analysis of charged particles and primarily, though not exclusively, to methods of and apparatus for the focusing and analysis of secondary charged particles resultant from bombardment of a target by high energy electron beams.

The bombardment of targets by high energy electron beams (e.g. 600 mev.) initiates the emanation of secondary charged particles which leaves the target at divergent angles. Furthermore, the secondary particles have different momentums, in many cases extending over a relatively large momentum spectrum or band. In order to analyze these secondary charged particles, various magnetic and electric particle deflecting systems have been devised. Presently available systems are capable of receiving monoenergetic particles emanating from the target source within a predetermined solid angle and can focus these monoenergetic particles at substantially a point image where a suitable detector can count the particles within a predetermined timed interval for purposes of analysis. However, particles of variant momentum traversing these same systems will become dispersed thereby complicating the detection system.

Accordingly, it is the general object of the present invention to provide a method of and apparatus for focusing charged particles emanating from substantially a point source so that all particles have a common focal point or image irrespective of their initial momentum or direction from such source, thus, ultimately enabling simplified particle analysis to be achieved.

More particularly, it is a feature of the invention to provide a focusing method wherein lateral deflection of the charged particles is effected in a manner such that the radial and transverse foci coincide and the radial momentum dispersion at the common focus is zero.

A further feature of the invention is the provision of a focusing method which can utilize magnetic or electric devices to establish the requisite particle deflecting forces.

Yet more particularly, it is a feature of the invention to provide a focusing method which, for various specific purposes, can utilize one or more magnetic or electric devices to establish a particular deflecting force pattern wherefore specifically desired particle trajectories can be achieved.

Additionally, it is a feature to provide a particle focusing method wherein particles of variant momentum traverse variant momentum-determined paths between the source and the focal point so that blocking of a certain segment of the particles at an intermediate position of their trajectories will provide momentum selection.

Yet another feature of the invention is to provide apparatus for effectively carrying out all of the above-mentioned features of the particle focusing and analysis method embodying the present invention.

These as well as additional objects and features of the invention will become more apparent from a perusal of the following description and explanation of the material depicted in the accompanying drawing wherein:

FIG. 1 is a radial ray diagram of monoenergetic particle trajectories from substantially a point source or object through a focusing system embodying the present invention so as to arrive at a common focal or image point,

FIG. 2 is a transverse ray diagram of monoenergetic particle trajectories through the same system from the object to the image,

FIG. 3 is a radial ray diagram of the trajectories of particles with the same angle of emission from the point source but with a finite spread of momentums,

FIG. 4 is a radial ray diagram of monoenergetic particle trajectories in a modified system embodying the present invention, and

FIG. 5 is a diagrammatic view of a particle analysis system embodying the features of the present invention and enabling the determination of particle mass.

With initial reference to FIG. 1, a particle P_0 emanating from a source **10** of charged particles is subjected to lateral deflecting forces so as to follow the curvilinear path or trajectory illustrated which defines a central orbit. Other charged particles P_1 and P_2, each having the same momentum as the particle P_0, emanate from the same source **10** but at divergent angles and are also subjected to lateral deflecting forces of a nature such that all particles having the same momentum and emanating from the same source **10** will be focused to a predetermined point image indicated at **12**.

In practice, the source **10** obviously has finite dimensions, but these can be maintained relatively small so that for purposes of the following discussion, such source **10** can be considered as substantially a point source.

The mentioned lateral deflecting forces can be established by electric or magnetic devices, bending magnets of more or less conventional design being quite commonly employed for this purpose. As illustrated in FIG. 1, two bending magnets **14**, **16**, or equivalent particle-deflecting devices, are each arranged to bend the particle P_0 traversing the central orbit in the same sense through an angle of approximately 110° so that a total angular deflection of 220° is experienced in the entire trajectory of this particle from the source **10** to the image **12**. Additionally, in accordance with the present invention, each magnet **14**, **16** is arranged to deflect the divergent particles P_1, P_2 through a greater or lesser angle such that a radial crossover point **18** is established a predetermined distance beyond the first magnet **14**. Considering this radial crossover point **18** as the center of the system, the magnets **14**, **16**, as illustrated, are arranged symmetrically on opposite sides thereof and are of substantially identical nature so that complete symmetry of the system is established. More particularly, in view of this symmetry, it can be easily recognized that the divergent particle P_1 will have a path length shorter than the path length of the central particle P_0 between the point source **10** and the crossover point **18**, but will have an equally longer path length than that of the central particle between such crossover point **18** and the final image **12**. Additionally, the other divergent particle P_2 will have a longer path length between the source **10** and the radial crossover **18** than the path length of the central particle P_0, but will, in turn, have a shorter path length between the crossover point **18** and the final image point **12**. In summary, it can be seen that in accordance with the present invention, all particles of the same momentum leaving the point source **10** and subjected to the deflecting forces of the magnets **14**, **16** or other deflecting devices will have the same path lengths between the point source **10** and the point image **12**. It will be obvious that only particles within a predetermined solid angle of emission will be accepted by the system but that this limitation is merely a practical and not a theoretical one.

If the system of FIG. 1 is viewed from the right and developed, the transverse particle trajectories of monoenergetic particles will appear as shown in FIG. 2. The central particle P_0 will pass directly from the source **10** to the image **12** while divergent particles P_3, P_4 will traverse paths which first diverge from the central path or trajectory

and thereafter converge to arrive at the previously described image point **12**. Thus, the illustrated system provides for coincident foci of both radially and transversely divergent rays of particles having the same energy or momentum. Various ways are known to establish this coincidence of the transverse and radial foci. One manner is described by D. L. Judd in the Review of Scientific Instruments, vol. 21, p. 213 in 1950, and is generally known as "gradient focusing." An alternative technique known as "wedge focusing" is described by K. T. Bainbridge in "Experimental Nuclear Physics" edited by E. Segre, published by John Wiley & Sons in 1953, vol. 1, p. 559 ff.

The manner in which radially and transversely divergent monoenergetic particles are brought to a common focal point having been established, the manner in which zero momentum dispersion at such focal point may be provided in accordance with the present invention must now be explicated. It has been determined that the momentum dispersion of particles emanating from substantially a point source is defined by:

$$\int_{\text{object}}^{\text{image}} Sh\,dt$$

where:

t is the distance from the source or object measured along the central orbit,

h is the curvature of a particle on the central orbit at position t, and

S is the deviation from the central orbit of a particle at position t and having the same momentum as the central orbit particle.

Consequently, if this integral is equated at zero, it can be seen that the momentum dispersion at the image or focal point will be zero to thus provide the necessary and sufficient condition for zero momentum dispersion.

With specific reference to FIG. 1, this necessary and sufficient condition for zero momentum dispersion at the image can be stated in a somewhat more physically obvious manner: if any two adjacent particles of the same momentum have the same path lengths between the object and image, then the system will have zero momentum dispersion. As has previously been explained with reference to the radial ray diagram of FIG. 1, the path lengths of the various particles of the same momentum in the illustrated system do have the same path lengths and thus the necessary and sufficient condition for zero dispersion at the image for this particular system is established.

If the bending magnets **14** and **16** of FIG. 1 are employed, this necessary and sufficient condition can be stated in yet another manner: if the net magnetic flux enclosed by two adjacent rays of the same momentum between the object and image is zero, then the momentum dispersion at the image will also be zero. It should be noted that if the two adjacent rays cross, as illustrated in FIG. 1, such crossing is equivalent to reversing the sign of the enclosed flux.

If the necessary and sufficient condition is established in a system such as illustrated in FIG. 1, the paths or trajectories of particles of variant momentum will appear substantially as illustrated in FIG. 3. As there shown, three particles P_0, P_5 and P_6 emanate from the point source **10** in the same direction, but the particles P_5 and P_6, respectively, have greater and lesser momentum than the central orbit particle P_0. As a result of their differing momentum, the deflecting forces of the first magnet **14** will cause a divergent of the particle paths or trajectories, but subsesequently, exposure to the deflecting forces of the second magnet **16** will have an opposite effect so that the particles will be bent by the deflecting forces into convergent paths so as to intersect at the radial focus or image **12**. Thus, ultimately, it will be seen that all charged particles from the point source **10** passing through the described deflecting system will have a common focal point (image) irrespective of their initial momentum or direction from the point source.

Having thus established the conditions for coincidence of the radial and transverse foci and zero momentum dispersion at such common focus, the improved focusing methof of the present invention simply entails subjecting charged particles emanating from a point source to lateral deflecting forces such that monoenergetic particles are focused to a point image and follow substantially curvilinear paths to satisfy the condition that:

$$\int_{\text{object}}^{\text{image}} Sh\,dt=0$$

As specifically delineated in the system shown in FIGS. 1, 2, and 3, the method entails the steps of first subjecting the charged particles emanating from substantially a point source to a first lateral deflecting force such that the particles follow a curvilinear path and monoenergetic particles pass through a radial crossover or intermediate focus and thereafter subjecting the particles to a second lateral deflecting force of like quantity and sense to the first force and symmetrically positioned relative to the crossover whereby monoenergetic particles come to a second focus or image and the total path lengths of particles of equal momentum between the source and image are equal, or in other words, the condition is satisfied that:

$$\int_{\text{object}}^{\text{image}} Sh\,dt=0$$

Such focusing method can, of course, be embodied in other systems. As one obvious modification, the two-magnet system explained hereinabove and illustrated in FIGS. 1, 2, and 3 can be readily transformed to a single magnet system by the juncture, in principle, of the two magnets so that the radial crossover, illustrated in FIG. 1, will lie within the single magnet. As in the two magnet system, the single magnet can be designed so that the radial and transverse foci coincide and the radial momentum dispersion at such common focus will be zero. The focusing method consequently is precisely the same in its broader aspects and differs only in details of the deflecting force application.

An additional modified arrangement embodying the invention so as to incorporate the zero momentum dispersion focusing method is illustrated in FIG. 4 where two magnets **20**, **22** or equivalent deflecting devices are utilized but are arranged to effect bending of the particles in opposite directions or senses. In this arrangement, the magnets **20**, **22** are symmetrically arranged about a midplane, indicated at **24**, but in order to establish the zero dispersion requirement entailing equal path lengths of monoenergetic particles emanating from the point source **26** in various directions, the deflecting forces must be applied so that no radial crossover between the two magnets is experienced. The radial and transverse foci can be made to coincide at a point image **28** in accordance with the principles first devised by Judd or Bainbridge, and in accordance with the present invention, the deflecting forces can be arranged so that all of the path lengths of the various monoenergetic particles will be equal to thus effect zero momentum dispersion at the common focal point or image **28**, as visually illustrated in FIG. 4.

While not illustrated, it will be also obvious that more than two magnets can be employed to embody the invention and carry out the described focusing method so that the transverse and radial foci coincide and the momentum dispersion at such focal point is zero. It is to be particularly noted that in the illustrated systems, a plane of symmetry is established, but this symmetry condition is not essential to the desired result of zero momentum dispersion as described. As long as the described integral

$$\int_{\text{object}}^{\text{image}} Sh\,dt$$

is equated to zero, zero momentum dispersion will be obtained. One additional feature may be mentioned that may not be entirely obvious from the illustrated systems. Since no restriction is made on the position of either the

object or image, these points can obviously be positioned at infinity and as a result, a parallel "beam" of particles entering the system will emerge as a parallel "beam" irrespective of the momentum of the individual particles.

The described focusing method lends itself admirably to particle analysis and by way of example of utilized in a mass spectrometer diagrammatically illustrated in FIG. 5. Such spectrometer has been described in detail in an article entitled, "Double Focusing Zero-Dispersion Magnetic Spectrometer" in the Review of Scientific Instruments, vol. 31, No. 5, pp. 556–564 in May of 1960, and details of its construction can be found in this article. Such spectrometer was designed for use with a linear electron accelerator (not shown) whose beam 30 of electrons having an energy of approximately 600 mev. was directed against a target 32 to effect the emission of secondary charged particles P, whose analysis was desired. The electron beam 30 generated by the accelerator consists of separated groups or bunches of electrons resulting from the characteristic operation of the accelerator which is energized by radio frequency energy having a frequency of 2856 megacycles. Thus, the emanation of secondary charged particles P occurs at spaced intervals in time. The method of focusing these particles corresponds to that described with regard to FIGS. 1, 2 and 3, and employs two 110° bending magnets 34, 36 disposed symmetrically to bend the particles P in the same sense and arranged to focus the particles regardless of their direction from the target 32 or their initial momentum to substantially a point image whereat a suitable particle detector 38 is located.

At the radial crossover between the two magnets 34, 36, members 40 defining a momentum-defining slit are disposed so that as a result of the momentum spread, best illustrated in FIG. 3, only particles within a selected momentum spectrum or band can pass therethrough and reach the detector 38. Obviously, the position of the members 40 can be changed to vary the size of the slit wherefore more or fewer particles will be blocked and a narrower or broader momentum band thus be permitted to reach the detector 38, as the case may be.

Additionally, between the first magnet 34 and the members 40, the particles are caused to pass through a resonant cavity 42 that is excited by the same radio frequency energy that drives the accelerator itself, wherefore electric fields are established in such cavity in timed relation to the emanation of charged particles P by the bombardment of the target 32 by the bunched beam 30 of electrons. More particularly, radio frequency energy is fed into the cavity 42 so as to excite the same in the $T.M._{012}$ mode that establishes electric fields adapted to transversely deflect particles P traversing the cavity an amount which depends upon their time of arrival therein. Particles P leaving the target 32 at a desired velocity will suffer no transverse deflecting forces while particles of either greater or lesser velocities will be transversely deflected and will subsequently be blocked by the members 40 of the previously described momentum selector. Consequently, this microwave cavity 42 operates as a velocity selector, permitting only particles P of predetermined velocity to pass therethrough without deflection so that they may subsequently traverse the slit and reach the detector 38. A phase shifter 44 is placed in the radio frequency input to the cavity 42 to enable establishment of the deflecting electric fields at the appropriate time so that the desired particle velocity is selected.

Since momentum and velocity selection are both achieved by the arrangement illustrated in FIG. 5, and momentum is equal to the product of mass and velocity, the precise measurement of velocity and momentum provides for the ready determination of the particle mass.

From the foregoing description of the mass spectrometer of FIG. 5, it will be understood that the previously described focusing method can with but the addition of the steps of velocity and momentum selection become a method for particle analysis. More particularly, the particle analysis method entails the steps of the previously described focusing method and the additional step of periodically establishing time-varying transverse deflecting forces in timed relation to the emanation of particles from the target and the further step of blocking the traverse of a certain segment of the particles so that only particles within a predetermined momentum and frequency range reach the detector.

Obviously, various other modifications in the described focusing and analysis methods and in the systems embodying those methods can be made without departing from the spirit of the present invention; and accordingly, the foregoing description of certain specific arrangements is to be considered as purely exemplary and not in a limiting sense; and the actual scope of the invention is to be indicated by reference to the appended claims.

What is claimed is:

1. The method of focusing charged particles emanating from substantially a point source which comprises subjecting the charged particles to a first lateral deflecting force such that the particles follow predetermined substantially curvilinear paths, and thereafter subjecting the charged particles to a second lateral deflecting force disposed in predetermined relationship to the first force such that the particles follow additional predetermined curvilinear paths and monoenergetic particles are focused to a point image and the condition is satisfied that:

$$\int_{\text{object}}^{\text{image}} Sh\,dt=0$$

wherein t is the distance from the source or object measured along the central orbit, h is the curvature of a particle on the central orbit at position t, and S is the deviation from the central orbit of a particle at position t and having the same momentum as the central orbit particle, wherefore the momentum dispersion at the image is zero.

2. The method of focusing charged particles according to claim 1 wherein the first and second deflecting forces are equal and are symmetrical about a predetermined plane therebetween.

3. The method of focusing charged particles according to claim 1 wherein the deflecting forces bend the particle trajectories in the same direction or sense.

4. The method of focusing charged particles according to claim 1 wherein the deflecting forces bend the particle trajectories in the opposite sense.

5. The method of focusing charged particles emanating from substantially a point source which comprises subjecting the charged particles to a first lateral deflecting force such that the particles follow predetermined curvilinear paths and monoenergetic particles come to an intermediate focus, and thereafter subjecting the charged particles to a second lateral deflecting force of like quantity and sense to the first force and symmetrically positioned relative to the first force about the intermediate focus whereby monoenergetic particles come to a second focus or image, the entire particle paths being such that the condition is satisfied that:

$$\int_{\text{object}}^{\text{image}} Sh\,dt=0$$

wherein t is the distance from the source or object measured along the central orbit, h is the curvature of a particle on the central orbit at position t, and S is the deviation from the central orbit of a particle at position t and having the same momentum as the central orbit particle.

References Cited in the file of this patent

UNITED STATES PATENTS

2,950,388	White	Aug. 23, 1960
3,031,596	Leboutet et al.	Apr. 24, 1962
3,056,023	Marshall	Sept. 25, 1962