

Oct. 18, 1949.

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METHOD AND APPARATUS FOR CONTROL OF BEAM ENERGY

Filed Aug. 13, 1945

3 Sheets-Sheet 1

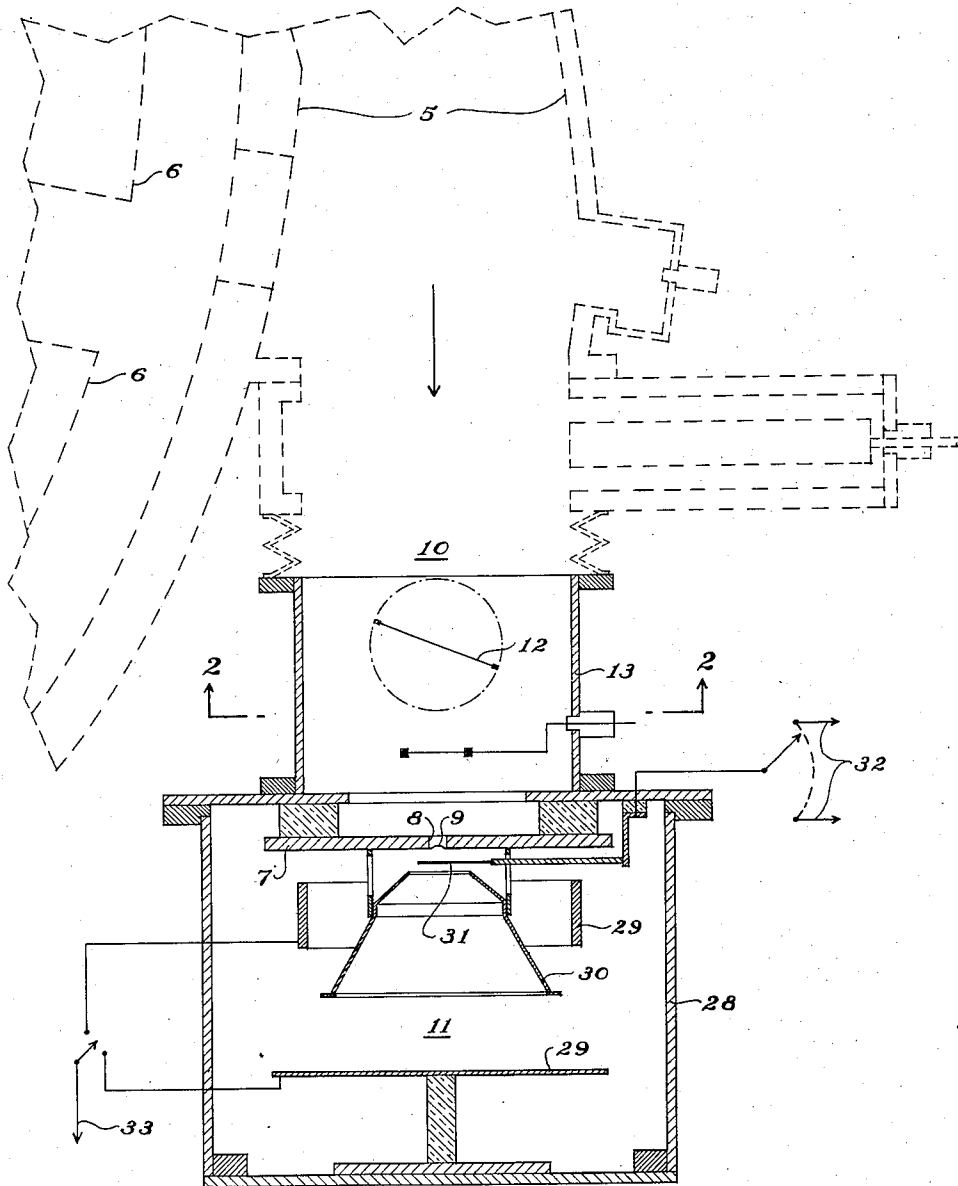


Fig. 1

WITNESSES

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3 Sheets-Sheet 2

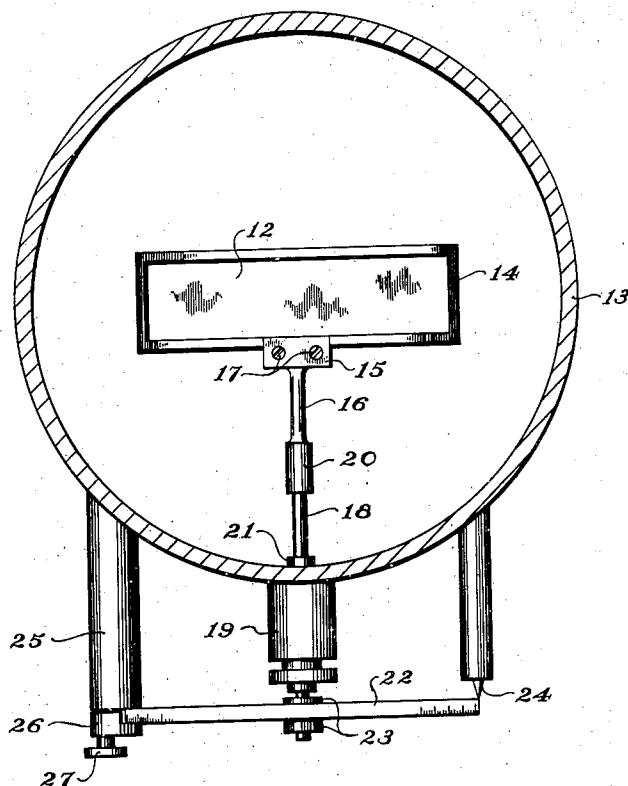


Fig. 2

WITNESSES

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3 Sheets-Sheet 3

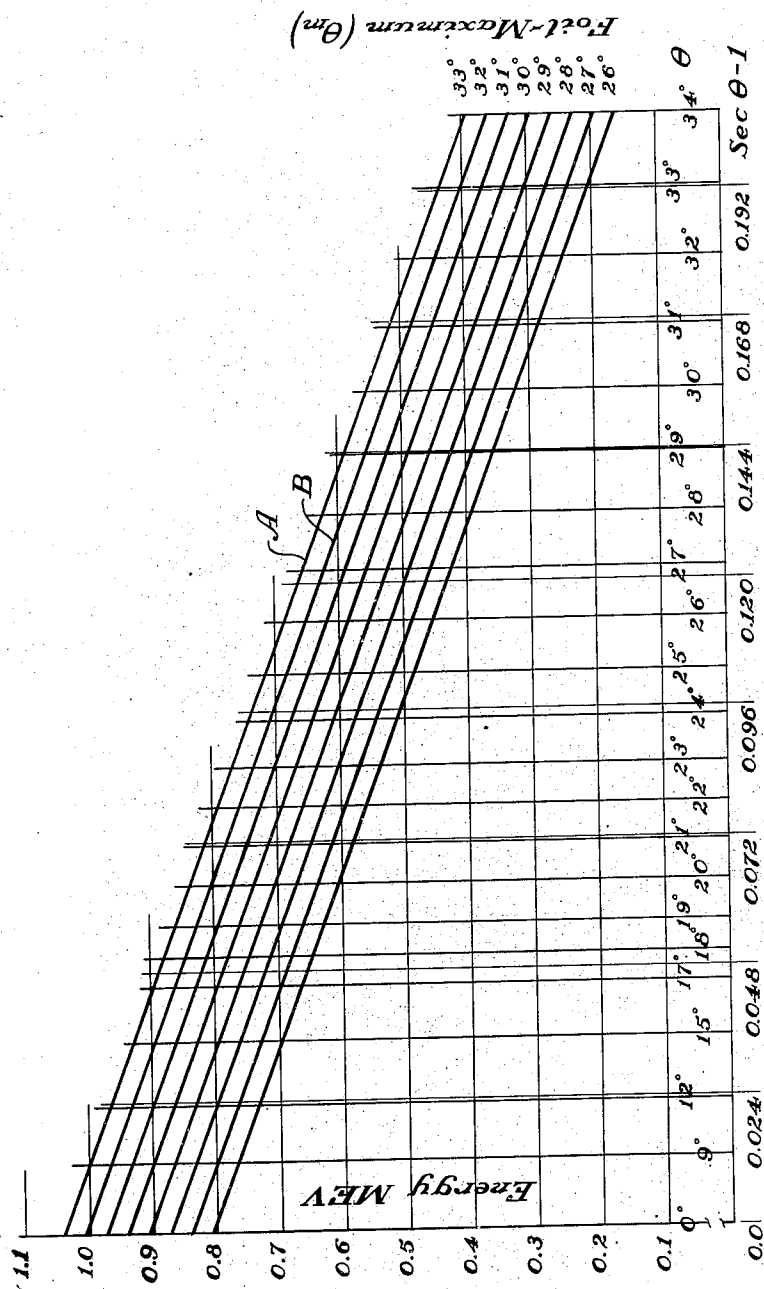


Fig. 3

WITNESSES

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METHOD AND APPARATUS FOR CONTROL
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Application August 13, 1945, Serial No. 610,644

8 Claims. (Cl. 250—86)

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This invention relates generally to the field of physics and more particularly to improvements in methods and means for controlling accelerated charged particles and the like.

Many types of charged particle accelerating devices or atom smashers (to use a commonly accepted term) are known which are useful in the production of monokinetic charged particle beams. Others exist in which the beam energy varies in distribution depending upon a number of factors. In the field of nuclear physics were accelerating devices of the type mentioned have received widespread use in atomic transmutation and/or disintegration operations, the control of the intensity and energy of the accelerated charged particle beam is an extremely important factor. Similarly, the problem of separating from the charged particle beam molecular ions and other undesired ions which affect the particular operation has been the subject of widespread inquiry and research. For example, it is now well known that the interposition of various types and thicknesses of foils or screens possessing various degrees of opacity or absorption in the charged particle beam, either before or after it emerges from the accelerator, is useful in controlling the intensity and energy of the bombarding ion beam. Such foils or screens may be of many materials, for example, aluminum, mica, gold, copper, brass or the like.

Many mathematical formulas, based upon theoretical and empirical considerations have been evolved in connection with the penetration through such foils by beta rays, gamma rays and accelerated charged particles of many types. For example, the absorption of beta rays by aluminum has been determined in the past to follow the rule:

$$R = 0.536E - 0.165$$

in which R is the range or thickness of aluminum which is just penetrable and is measured according to the more usual practice in the art in grams per square centimeter. Similarly tables of absorption coefficients and ranges have been prepared and published for various materials as a function of incident gamma ray energy, as well as for other charged particles such as protons, deuterons, alpha particles and/or the like.

It is apparent, however, that while the use of a multiplicity of foils to reduce the intensity of a beam of charged particles may give the desired results, an operation which requires the determination of a series of effects based upon a corresponding series of intensities or beam currents

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would require an excessive amount of expensive equipment together with the delays attendant upon the positioning of the foil or absorber in proper relation with the beam. Furthermore, determinations based upon small increments of energy become almost impossible to accomplish or at best require foil preparation techniques beyond the capacity of the average person skilled in the art.

Another problem noted above concerns itself with the elimination of undesired particles from a beam which in many cases in effect amounts to a mass separation process. In disintegration operations it is necessary to be certain that only a particular charged particle is effective in bombarding the target element as well as that it is desirable that the bombarding particle be monokinetic. Thus for example, in operations involving the use of a highly accelerated beam of protons, it is found that so-called molecular hydrogen ions are produced in the ion source as well as the expected proton. Since such a molecular ion possesses a unit charge as does the proton, in a device such as a Van de Graaff accelerator the kinetic energy given to each type of particle will be the same. However, the velocity of the molecular ion is lower and upon splitting when bombarding the target, two lower energy protons are produced which may affect the particular disintegration operation adversely. Various schemes have been advanced such as magnetic analyzers and the like, which have been found somewhat effective in deflecting undesired ions such as molecular ions from the target zone. Such analyzers, however, are comparatively expensive in construction and operation and only serve to encumber the accelerating device.

As a further consideration, the undesired particles may have the same charge to mass ratio as the desired ones and will have the same terminal velocity in a device such as mentioned immediately above. Therefore, even if a cyclotron type of accelerating device is employed, which, by reason of the principles upon which its operation is based, would eliminate the molecular ions such as were previously mentioned, any particles having the same charge to mass ratio as the desired bombarding particles would by the same principles be equally accelerated.

It will therefore be seen that this invention has as a broad object the provision of an improved method and means for controlling beam currents and beam energies.

Another object of the invention is the provision of a unique type of foil of variable thickness

useful in charged particle accelerating devices for controlling the beam energy or intensity.

A further object is the provision of a single foil which will permit small increment control to be imposed.

A still further object of this invention is to provide an effective method for the separation of undesired particles from an accelerated charged particle beam.

Other objects and advantages will be come apparent from the following discussion and detailed description and explanation of the operation of an illustrative embodiment.

The above stated objects are accomplished and the desired results, eliminating the shortcomings of prior art devices, are attained by interposing a plane absorbing foil of predetermined thickness in the beam the said foil being adapted to be rotated about a line perpendicularly intersecting the axis of the beam, thereby permitting variation of the thickness of the foil presented to the beam and the deflecting angle which is effective in separating undesired particles from the beam.

For the purpose of illustration of the principles involved and noting that no limitation on the scope of the invention should be imposed thereby, assume a foil of a suitable absorbing material having plane dimensions greater than the transverse cross sectional dimensions of the beam, and a thickness of a predetermined air equivalent and expressed linearly, for example, five thousandths of an inch. If such a foil is interposed in an accelerated charged particle beam in a plane perpendicular to the axis of the beam, the amount of absorption can be readily determined by the use of experimental methods or the empiric formulas mentioned above. When the foil is rotated about an axis which intersects the beam axis perpendicularly then the absorbing thickness presented to the beam varies as the secant of the angle through which the beam is rotated. The new thickness presented to the beam is equal to the original thickness multiplied by the secant of the angle of rotation and as a consequence the foil is referred to as a secant foil.

It will then be apparent that the variation of beam energy can be readily accomplished in a simple and direct manner and that the increments of thickness may be readily added without recourse to a multiplicity of foils having a multiplicity of thicknesses. In fact, the thickness, absorption or stopping power of the foil (the terms being used synonymously) may be varied during the operation of the beam thereby permitting a greater degree of flexibility in the operation. The exact determination of the added or increment of thickness is only a matter of the evaluation of the equation:

$$\Delta t = t \secant \theta - t = t (\secant \theta - 1)$$

in which t is the thickness of the foil, Δt is the thickness increment gained by rotating the foil and θ is the angle between the normal to the plane of the secant foil and the beam direction, or as noted above the angle through which the foil is rotated. In the case of a charged particle beam, the use of absorbing metals or mica or other materials for the secant foil readily suggest themselves to one skilled in the art and no claim is made herein to so-called nuclear absorbing materials per se. The choice of a particular material and the original thickness of the foil depend entirely upon the operation being undertaken and the type of charged particle and/or radiation that is being employed. Thus, for example, a

cadmium foil may be found useful in an operation involving gamma rays or an aluminum foil in the case of beta rays.

Similarly, as has been noted, the method may be adapted to control of a beam of light, the intensity and other characteristics of which may be varied through the use of a rotatably mounted optical filter or the like, which, though a certain amount of reflection may be caused by the angular incidence of the beam upon the filter and for which correction factors may be used, the effective thickness of the filter may be increased or decreased at will and to a known amount.

Now when such a foil as hereinbefore briefly described is mounted in a charged particle accelerating device such as a cyclotron, in advance of the exit aperture, so that the energy of the emergent beam may be controlled, it has been found that at an angular setting with respect to the beam axis, the composite or molecular ions impinge upon the foil and do not pass through it as do true atomic ions, but are deflected, absorbed, scattered or otherwise filtered out of the beam, more or less in a manner of a portion of a light beam impinging upon an angularly disposed filter. This characteristic is extremely important and permits the elimination of substantially all undesired ions from a charged particle beam before emergence of the beam from the accelerating device, or at least before bombardment of the target material.

The mountings contemplated for the secant foil generally described above may be varied and many types of indicating means to indicate the degree of angularity or rotation will suggest themselves for the various operations for which the secant foil may be employed. It may be found useful as well, to employ automatic devices and/or electronically activated ones to control the angle so that a predetermined beam energy or other desired effect may be maintained. However, for the purposes of simplicity of explanation, a more detailed description will be given of a manually operated secant foil as embodied in a cyclotron type of accelerating device. Such an embodiment together with explanatory experimental curves taken during the operation thereof are shown in the drawings which are made part of this specification and in which—

Figure 1 is a schematic representation of a portion of a cyclotron charged particle accelerating device showing the location of the secant foil and other elements in the exit and target zones.

Figure 2 is an elevational view partly in section showing details of the construction of a manually operated secant foil, taken on line 2—2 in Fig. 1.

Figure 3 is a chart on which portions of curves showing the relation between the energy of the emergent beam and the angular setting of the secant foil are plotted.

Referring to the drawings and more particularly Figure 1, the cyclotron structure comprises generally the tank 5, which is sealed and maintained internally in a subatmospheric state, the hollow shell-like semicircular accelerating electrodes 6, and the exit aperture plate 7, in which the aperture 8, is covered by a sheet metallic foil 9, to maintain the vacuum within the tank 5. The zone 10, inward of the exit foil for purposes of clarity, will hereafter be referred to as the exit zone of the cyclotron; and the zone 11, outward of the exit foil will be referred to as the target zone. Within the zone 10, and more particularly within the tubular portion 13 thereof, and spaced

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from the exit plate 7, the secant foil generally denoted as 12, is positioned so that it is adapted to be rotated to any diametrical position in the broken line circle shown in the drawing and intercept the beam, the direction of which is indicated by the arrow. Since accessories such as the auxiliary foils, gate-valves and the like do not form part of the present invention, no detailed description of them will be given.

In the particular embodiment now being described, the secant foil 12, is constructed as follows: reference being made now to Figure 2. A thin rectangular sheet of mica having a normal uniform thickness of about 8.5 milligrams per square centimeter is stretched in a rectangular frame 14, which consists of 2 congruent portions adapted to be held together in laminar fashion by a multiplicity of screws (not shown) and to retain the mica foil therebetween. Clamping blocks 15, are soldered or otherwise rigidly attached to frame laminations 14, and are provided with cooperating machined portions to accommodate the spindle shaft 16, which is held rigidly in place by tightening the screws 17. A push-through shaft 18, and a seal 19, which acts as a bearing for the shaft 18, and permits rotation thereof, without deteriorative air leakage into the vacuum system within the cyclotron, substantially complete the foil structure and support. The shafts 18 and 16, are rigidly coupled by means of the tubular shaft coupling 20, which is preferably provided with set screws (not shown) to accomplish locking of the respective shafts. A collar 21, which cooperates with a spot-face in the inner surface of the tubular portion 13, acts as a thrust bearing and limits longitudinal movement of the shafts 16 and 18.

The air-seal 19, is of a standard type now well known in the art and generally referred to as a Wilson seal. Since many variations in such seals exist, no detailed description will be given beyond noting that the seal should be one which permits rotation of the foil and prevents air leakage into the cyclotron. A protractor disc 22, suitably calibrated in degrees and fractions of degrees, for example, starting at a zero central position and with the numbers increasing to ninety degrees on either side of the zero calibration is rigidly mounted on the outwardly extending threaded end of shaft 18, and locked in position by means of the cooperating threaded collars 23. An indicating pointer 24, is mounted on the tube 13, and extends downwardly therefrom to a point adjacent to the calibrated portion of disc 22. A cylindrical extension 25, is provided with means operative to clamp the disc 22, in a predetermined fixed position, is similarly mounted on the tubular portion 13. The locking action is accomplished by providing a shouldered locking portion 26, drilled to accommodate the screw 27, which engages a threaded recess in the rod 25, and a shoulder machined to permit rotation of the disc 22, when portion 26, is loosely held by screw 27. Upon tightening the screw 27, the shoulder portion clamps the disc 22 against the lower end face of rod 25, and prevents further rotation of the disc.

In assembling the foil structure and more particularly in mounting the disc 22, care should be taken that the foil is normal to the beam axis when the indicating pointer 24, indicates the zero position so that the angle θ can be read directly from the disc calibrations. This precaution, of course, is only to enable the user to simplify readings, that is, to make the use of a correction fac-

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tor unnecessary, and is not a limitation on the operation of the device.

The operation of the foil and its utility for the accomplishment of the purposes hereinabove stated will be explained in connection with a transmutation process in which tritium atoms (i. e. the atoms of the hydrogen isotope of mass three) are ionized and accelerated and employed to bombard deuterium atoms to produce helium nuclei and neutrons.

The deuterium gas was introduced into the target zone 11, which is defined by the disintegration chamber 28 and the aperture plate 7. Collecting electrodes 29, collimating elements 30, and probe electrode 31, disposed within the disintegration chamber permit electronic measurements to be taken during the transmutation process, the electronic indicating and recording circuits being denoted at 32 and 33. Since these elements are not considered part of the present invention their function and operation will not be discussed in detail beyond the description necessary for a complete understanding of the present invention.

Tritium ions were produced in a suitable source disposed at the center of the cyclotron apparatus and not shown in the drawings. The mixture introduced into the ion source contained a primary concentration of about 0.025% of tritium atoms in sixty cubic centimeters of hydrogen and deuterium gas at normal temperature and pressure; the primary mixture was then added in a ratio of 1:1000 to ordinary tank hydrogen gas prior to ionization. Such a mixture resulted in a beam of about 5×10^5 accelerated tritium ions at the secant foil 12.

The proper cyclotron adjustments of the magnetic field and radio-frequency accelerating potential were made to insure acceleration of particles having only the same charge to mass ratio as tritium, and thereby effectively eliminate from the bombarding beam undesired atomic ions introduced by the dilution of the tritium gas noted above.

With the secant foil in position, it was found that when using a mica foil 8.5 mg./cm.² in the thickness, the energy of the particles reaching the target zone could be varied by varying the angle θ as indicated on the disc 22.

An indication of the amount of variation and control possible may be had from the chart shown in Figure 3 in which the ordinate shows energy values of the bombarding tritium ions detected in the target zone 11, by the use of the probe electrode 31, and associated electronic circuits 32, and the methods described in and claimed in the copending U. S. patent application of Marshall G. Holloway, S. N. 627,268 filed November 7, 1945. The angular position of the foil is shown as the angle θ (as defined above) in degrees as the abscissa and an alternative calibration in terms of secant $\theta - 1$ is also shown to permit rapid thickness computations.

Since the maximum ionization produced in the zone 11 and particularly in the region of electrode 31 will depend on the energy of the particles before the beam impinges upon the foil 12 and will vary as operating conditions of the cyclotron vary from time to time; and the said maximum will occur at varying absorbing foil thicknesses depending upon that energy, a number of curves are shown each being labelled with the angular setting at which the maximum ionization is detected. This latter factor permits an exact evaluation of the energy of the particles reaching the target zone during any particular run.

The energy of the bombarding particles as shown in the chart may be readily shown to be the solution of the equation:

$$E = E_0 - K (\sec \theta - 1)$$

in which E is the energy of the bombarding particle beam at any angle, θ , E_0 is an empirical constant and represents the energy of the beam entering the target chamber with the foil plane perpendicular to the beam, K is a constant depending upon the thickness and stopping power of the foil, and θ , as has been heretofore defined, is the angle between the normal to the plane of the foil and the axis or direction of the beam.

It should be noted that the accuracy of control is indicated by the fact that K which is in effect the slope of the energy against (secant $\theta - 1$) curves shown in Figure 3, was found to have the same value though the energy of the beam impinging on the secant foil varied. The spacing between the curves, for example curves A and B, was readily determined even though the value of E_0 varied depending upon the cyclotron adjustments by establishing a relation between E_0 and θ_m , i. e. between the energy of the beam arriving at the foil and the angle at which ionization was a maximum. Thus by using the chart in order to find the incident energy of a particle for any foil setting θ , it is only necessary to follow the line (i. e. curve A, B, etc.) appropriate to the angle θ_m existing at that time to the value of (secant $\theta - 1$).

During the disintegration operation, due to the dilution of the tritium gas in the hydrogen-deuterium mixture, particles consisting of, for example, a hydrogen nucleus and a deuterium nucleus were accelerated since they have the same charge to mass ratio as the tritium. Such composite particles would result in a different reaction upon bombardment of the target material, i. e. the deuterium in zone II, than the reaction obtained by bombardment with tritium ions. It was found that by adjustment of the cyclotron to obtain maximum acceleration of particles of the charge to mass ratio of tritium and by proper setting of the foil at a particular angle θ , a substantial elimination of the undesired composite particles from the target zone was obtained. It is believed that some of these composite particles were deflected in the manner of part of a light beam upon striking an angularly disposed filter and that others upon splitting when striking the foil II, (with consequent lower energy of the splitting process products) were absorbed therein, or otherwise effectively prevented from emerging through the foil disposed over the aperture 8.

While a particular embodiment of the invention has been described together with a typical operation demonstrating the utility of the principles and structures, the broadness of the scope of application thereof should not be limited. Many variations have already been noted as to materials, structural features and diversity of the fields of employment, and others will suggest themselves to one skilled in the art, however, it is intended that no limitation should be placed hereon by reason of the specific details disclosed nor by the physical principles expressed herein and believed to be true. The means and methods disclosed have been found to be useful for the purposes stated and limitation thereof should be by the claims alone.

What is claimed is:

1. In apparatus for the acceleration of charged particles in a beam, including an accelerating

zone, an exit zone and a target zone, the combination of an absorbing foil, means supporting said foil in energy absorbing relationship with the accelerated charged particle beam in advance of said target zone, said supporting means being adapted to permit rotation of said foil about an axis perpendicular to the axis of said beam whereby the absorbing thickness presented to said beam may be varied.

2. In apparatus for the acceleration of charged particles in a beam, including an accelerating zone, an exit zone and a target zone, the combination of a plane absorbing foil of uniform thickness, means supporting said foil in energy absorbing relationship with the accelerated charged particle beam in advance of said target zone, said supporting means being adapted to permit rotation of said foil about an axis perpendicular to the axis of said beam whereby the absorbing thickness presented to said beam depends on the angular disposition of the plane of said foil with respect to the direction of said beam.

3. In apparatus for the acceleration of charged particles in a beam, including an accelerating zone, an exit zone and a target zone, the combination of a plane absorbing foil of uniform thickness, means supporting said foil in energy absorbing relationship with the accelerated charged particle beam in advance of said target zone, said supporting means being adapted to permit rotation of said foil about an axis perpendicular to the axis of said beam whereby the absorbing thickness presented to said beam depends on the angular disposition of the plane of said foil with respect to the direction of said beam, and means for indicating the angular relationship between the plane of said foil and the direction of said beam.

4. In apparatus for the acceleration of charged particles in a beam including an accelerating zone, an exit zone and a target zone, the combination of a plane absorbing foil of uniform thickness, means supporting said foil in energy absorbing relationship with the accelerated charged particle beam in advance of said target zone, said supporting means being adapted to permit rotation of said foil responsive to the energy of said beam detected in said target zone whereby the energy of said beam in said target zone is maintained constant, and means for indicating the angular relationship between the plane of said foil and the direction of said beam.

5. Mass separation apparatus comprising in combination, means for producing ions of the materials to be separated, means for accelerating said ions in a high velocity beam, a plane uniform thickness absorbing foil, means supporting said foil in the path of said accelerated beam, said supporting means being adapted to permit rotation of said foil about an axis substantially perpendicular to direction of said beam and setting of said foil so that the plane face thereof is in predetermined angular relationship with respect to the beam axis whereby undesired ions are separated from said beam, and collecting means including a zone in which the desired ions are collected.

6. In mass separating apparatus comprising an ion source, means for accelerating the ions in a beam and a collecting zone for the desired ions, the combination of a plane, uniform thickness absorbing foil, means for adjustably supporting said foil in predetermined angular relationship with respect to said beam whereby molecular ions are eliminated from said beam, and means for

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indicating the angular relationship between the plane of said foil and the direction of said beam.

7. The process of separating elements which comprises introducing in ion form a combination of elements containing the desired element into an apparatus for the acceleration of ionized particles, accelerating the ionized particles having the same charge to mass ratio, causing the beam of said highly accelerated ionized particles to impinge upon a plane, uniform thickness absorbing foil, disposed at a predetermined angle to the direction of the said beam whereby undesired and molecular ionized particles are deflected and absorbed, and collecting the desired particles which penetrate said foil in a separated zone.

8. The process of separating tritium which comprises ionizing a gaseous mixture containing tritium, introducing the gaseous ions into an accelerating apparatus, accelerating the gaseous ionized particles having the same charge to mass ratio as the tritium ions in said accelerating apparatus, causing the beam of highly accelerated ionized particles to impinge upon a plane, uniform thickness absorbing foil set at an angle to the

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direction of the beam whereby molecular ionized particles and undesired particles are deflected and absorbed, and collecting the desired ionized tritium particles which penetrate said foil in a separated zone beyond the exit foil of said accelerating apparatus.

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