(12) UK Patent Application (19) GB (11) 2 132 000 A

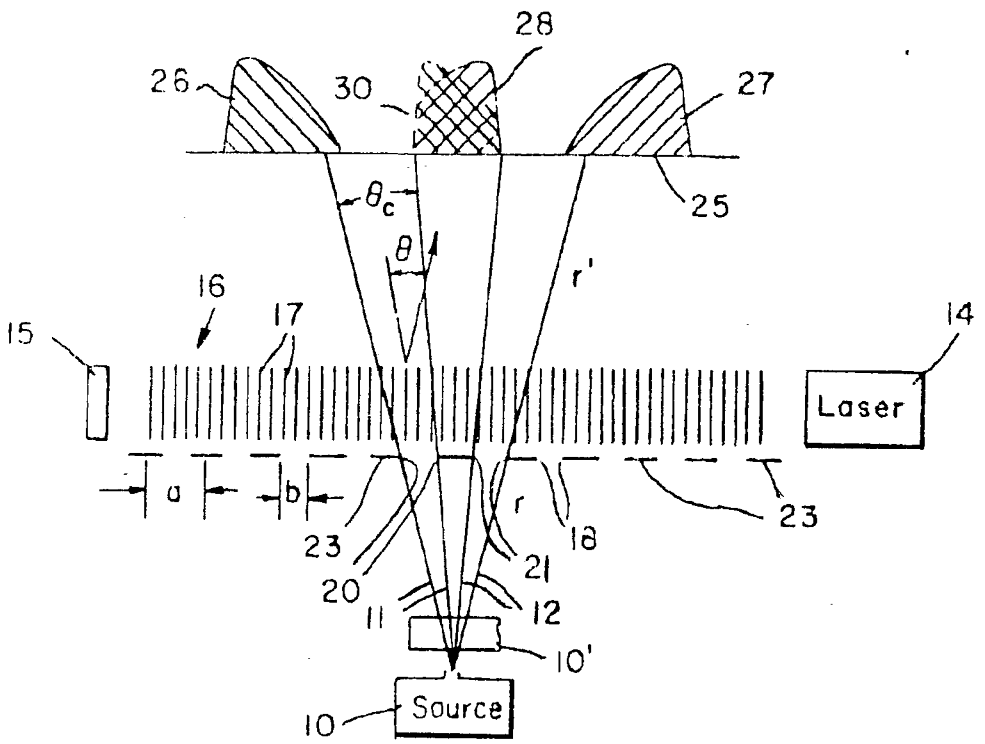
(21) Application No **8232068**
(22) Date of filing **10 Nov 1982**
(43) Application published **27 Jun 1984**
(51) INT CL[3] **B01D 59/00**
(52) Domestic classification **G6P** 8
(56) Documents cited
GB A 2059668
GB A 2053717
GB 1573508
GB 1501965
Cook Physical Rev. A Vol 18, No 6, 1978 Pages 2533-2537 see page 2 of present specification
(58) Field of search **G6P**

(71) Applicants
Litton Industries Inc., (USA-Delaware), 360 North Crescent Drive, Beverley Hills, California 90210, United States of America.
Saul Altshuler, 608 15th Street, Manhattan Beach, California 90266, United States of America.
(72) Inventor
Saul Altshuler
(74) Agent and/or Address for Service
Haseltine Lake & Co., Hazlitt House, 28 Southampton Buildings, Chancery Lane, London WC2A 1AT.

(54) Isotope separation by standing waves

(57) The separation of isotopes is accomplished by scattering a beam of particles (11,12) from a standing electromagnetic wave (16). The particles may consist of either atoms or molecules, the beam having in either case a desired isotope and at least one other. The particle beam is directed so as to impinge on the standing electromagnetic wave (16), which may be a light wave. The particles, that is, the atomic or molecular quantum-mechanical waves, see basically a diffraction grating corresponding to the troughs and peaks of the electromagnetic wave (16). The frequency of the standing electromagnetic wave (16) substantially corresponds to an internal energy level-transition of the desired isotope. Accordingly, the desired isotope is spatially separated by being scattered or diffracted.

Fig. 1



GB 2 132 000 A

Fig. 1

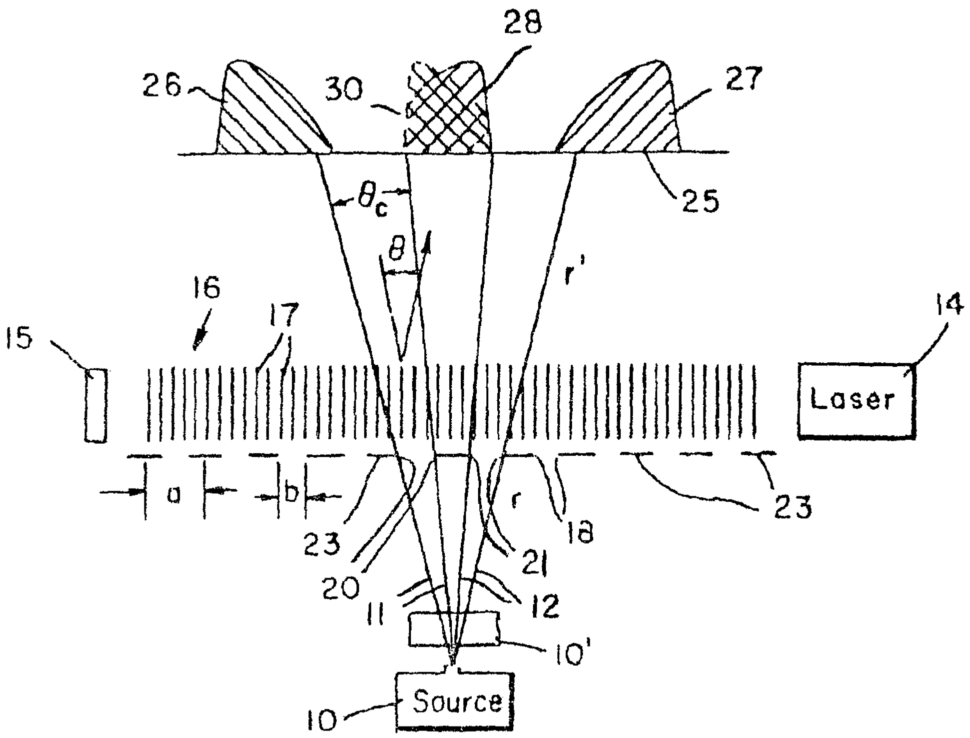
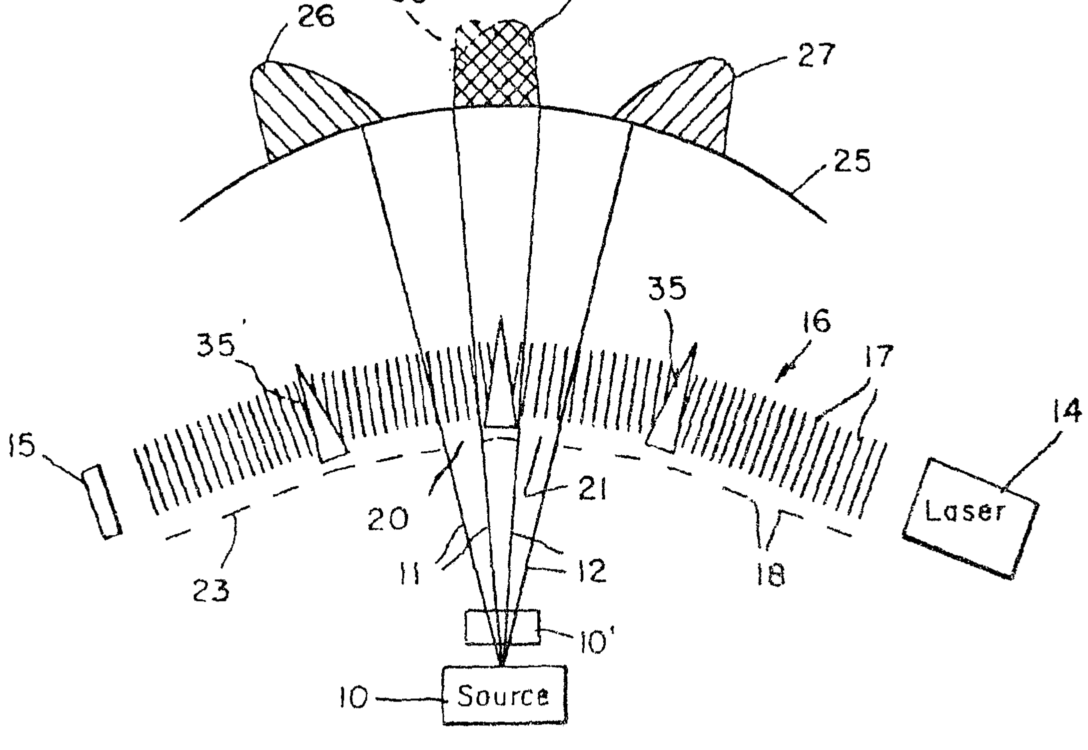

26
30
28
27
25
θ_c
θ
r'
16
17
15
14
Laser
a
b
23
r
18
23
20
21
11
12
10'
10
Source

Fig. 2


30
28
26
27
25
35
35'
16
17
15
14
Laser
20
21
23
11
12
18
10'
10
Source

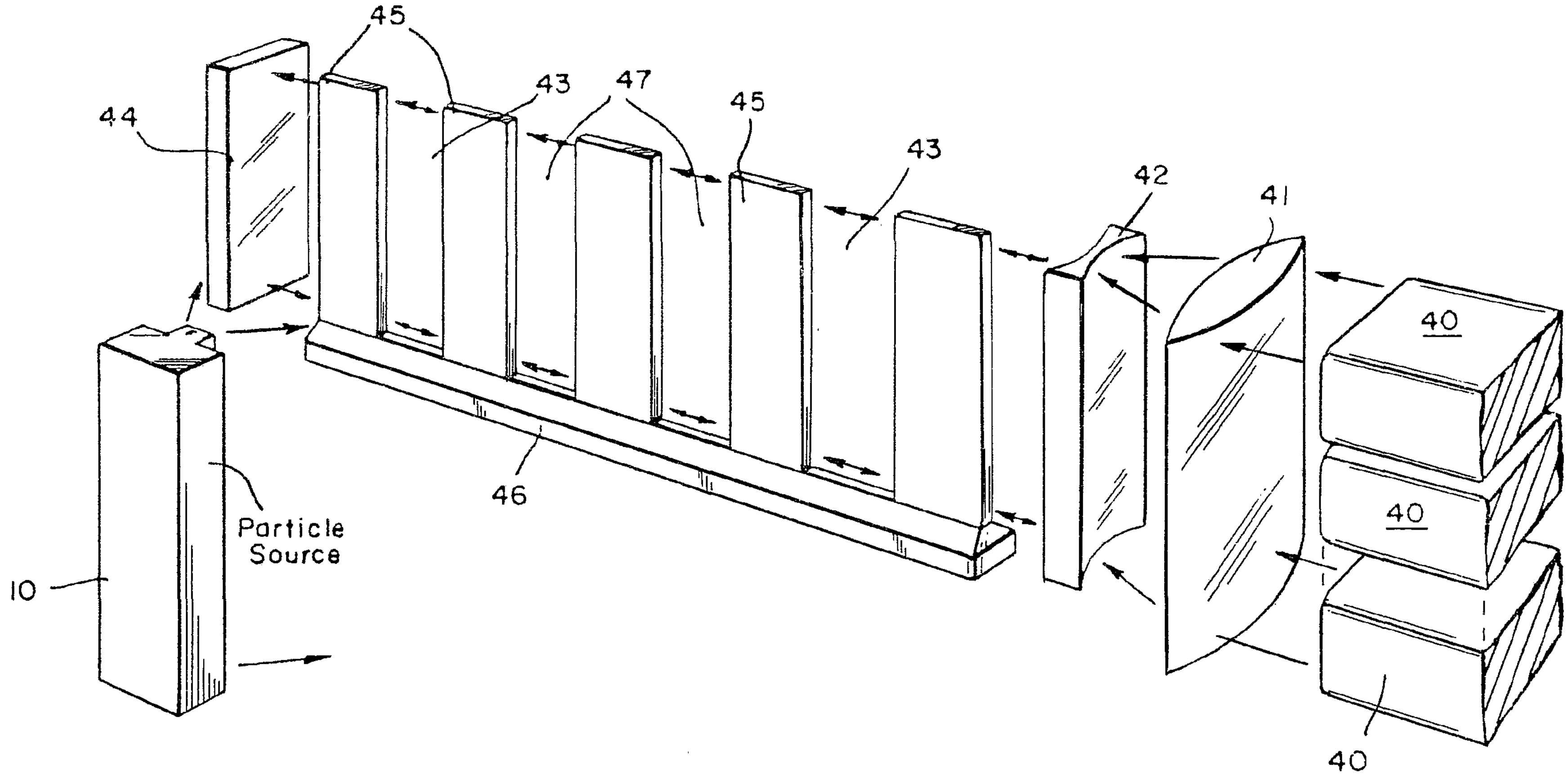


Fig. 3

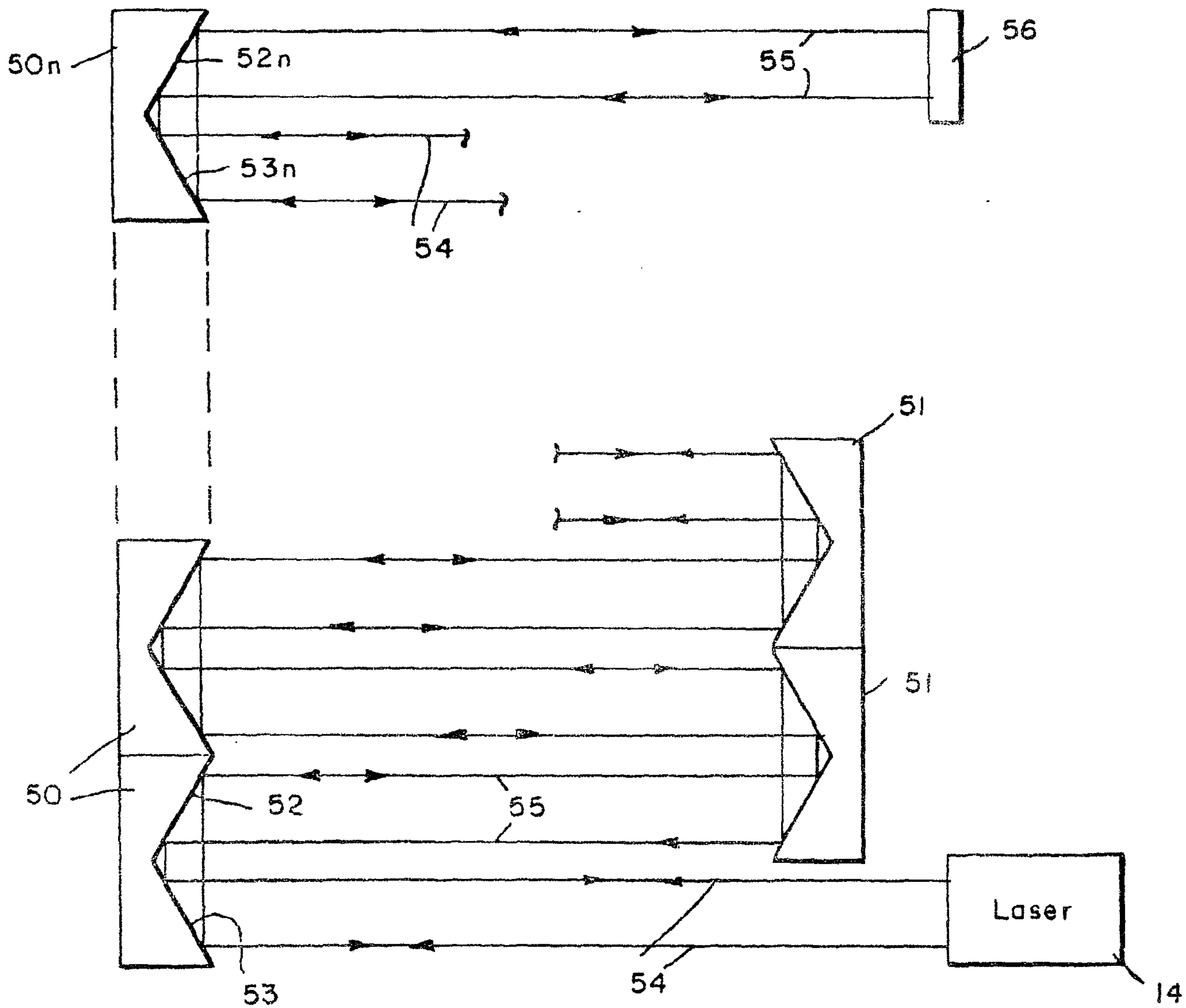


Fig. 4

SPECIFICATION

Isotope separation by standing waves

This invention relates to a method and apparatus which may be used for the separation of isotopes by standing waves.

Presently, many methods and types of apparatus are known for separating a desired isotope from one or more others. A presently used commercial process utilises gaseous diffusion whereby the isotopes are separated by their mass differences. Another commercial process achieves separation of the isotopes by centrifugal force.

Other promising approaches are the Dawson process, as exemplified by U.S. Patent No. 4,059,761 to John M. Dawson. Here the isotopes are differentially energised in a dense palsma by stimulating them at a resonant frequency. Another promising approach is the one jointly carried out by Jersey Nuclear-Avco Isotopes, Inc. A representative patent for this approach is U.S. Patent No. 3,772,519 to Levi, et al. Referring to the patent to Levi, reference is made to a paper entitled "Laser Separation of Isotopes", by Richard N. Zare, in the *Scientific American* of February, 1977, pp.86 through 98. Here a desired isotope is ionized by irradiating it with one or more lasers to remove an electron.

Reference is also made to the patent to Braunstein, Altshuler, and Frantz, U.S. No. 3,532,879. This patent discloses apparatus for deflecting atoms by a standing light wave. However, the neutral particle beam is directed towards the electromagnetic standing wave at the Bragg angle. In this connection, reference may also be made to a patent by Altshuler, et al., U.S. No. 3,761,721. In this patent a beam of particles may be split into two beams by the process disclosed in the above mentioned patent to Braunstein, et al.

The deflection of atoms by a resonant standing electromagnetic wave has been investigated in the recent scientific literature. Thus, a paper by Cook, et al., which appears in *Physical Review A,* Volume 18, No. 6, December 1978, pages 2533 to 2537, is a theoretical study to prove mathematically that such a deflection of atoms is possible. Another paper, by Arimondo, et al., which appears in *Physical Review Letters,* Vol. 43, No. 11, September 10, 1979, pages 753 through 757, relates to a laboratory experiment on a sodium beam to demonstrate the existence of the phenomenon that such a particle beam can be diffracted or scattered by a standing wave resonant to the internal excitation level of the atom.

It should be noted that neither of the two publications just referred to suggests the use of this phenomenon for the separation of isotopes; neither does either of the two papers propose that more than a single beam be used.

In accordance with one aspect of the present invention there is provided an apparatus for separating isotopes, comprising:

(a) means for generating a beam of particles having a desired and at least one other isotope;

(b) means for collimating the beam of particles into a plurality of beamlets;

(c) means for generating a standing electromagnetic wave, extending transverse the path of the particles, the said electromagnetic wave having a frequency substantially corresponding to an internal excitation level of the desired one of the isotopes, thereby to scatter particles of the desired isotope without substantially exciting the particles after scattering; and

(d) means for collecting the scattered particles, the particles forming substantially separated intensity peaks, substantially in the plane defined by the particle beam and electromagnetic wave.

According to another aspect of the present invention there is provided a method of separating isotopes comprising the steps of:

(a) generating a beam of particles including a desired and at least one other isotope;

(b) collimating the beam of particles into a plurality of beamlets;

(c) generating a standing electromagnetic wave extending transverse the path of the particle beam and having a frequency substantially corresponding to an internal excitation level of the desired one of the isotopes, thereby to scatter particles of the desire isotope and to spatially separate the desired isotopes from other isotopes into separate intensity peaks substantially in the plane defined by the particle beam and the electromagnetic wave; and

(d) collecting the scattered particles.

The particles may be either atoms or molecules.

In the case of atoms, it may be desirable to curve the standing electromagnetic wave about the circumference of a circle having a centre which substantially coincides with a point of origin of the beam so as to cause the beamlets to impinge on the wave at right angles. This may, for example, be accomplished by a plurality of prisms interposed into the path of the wave.

In the case of molecules, the standing wave may have a substantial height. That is, the standing wave field may be a sheet of light. This may be accomplished by one or more lasers or a plurality of mirrors which are so disposed as to reflect the laser wave back and forth. The electromagnetic wave should be quite thin, in order to produce a large diffraction of the atomic or molecular wave.

For a better understanding of the present invention and to show more clearly how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings in which:-

Figure 1 is a schematic representation of particle beamlets scattered by a standing electromagnetic wave showing the intensity of the desired isotope which has been scattered by the standing wave;

Figure 2 is a schematic representation similar to that of Figure 1, but showing the standing wave extending about a circle having its origin in the source of the particle beam;

Figure 3 is a perspective view of an apparatus for more efficiently separating isotopes capable of producing a standing wave of substanital dimensions; and

Figure 4 is a side elevation view of a laser and a plurality of mirrors for folding the path of a standing wave.

Referring to Figure 1, there is shown schematically an apparatus for performing isotope separation. There may be provided an oven 10, or alternatively, a supersonic nozzle 10′, the purpose of which is to generate a beam of particles as indicated by rays 11 and 12 included in the beam which beam spreads substantially linearly, as shown. Generally, when the particle beam consists of atoms, an oven 10 may be preferred. In some cases, particularly in the case of molecules, it may be desired to cool the molecule particle beam by a supersonic nozzle 10′. Of course, it will be understood that, when the original mixture of isotopes is a gas, it may not be necessary to heat the gas. By having the apparatus in a vacuum, the particle beam will not spread due to unwanted collisions.

In some conventional manner, for example by the use of a laser 14 and a mirror 15, which should be a totally reflecting mirror, a standing electromagnetic wave 16 is generated. The laser 14 also includes a reflecting mirror. Vertical lines 17 may, for example, represent the peaks or crests of the standing wave. The standing wave may be a light wave or some other electromagnetic wave, depending on the energy of the internal excitation level of the desired isotope.

The beam is collimated by providing a plurality of collimating slits such as 18, 20, 21, which are formed by a plurality of obstructions or baffles 23. As shown in Figure 1, the width of each slit is *b*, and the distance between the centres of adjacent baffles 23 is *a*.

The slit 20 collimates a portion of the beam, as defined by rays 11, which passes to a collector 25, which may simply be a plane sheet of a suitable material. The slit 21 collimates another portion of the beam, as defined by rays 12, which also passes to the collector 25. After passing through the collimating slits, the beam forms a plurality of beamlets. Figure 1 illustrates the intensity distribution 26, 27 and 28 of the desired isotope which is scattered by the slit 21.

It will be understood that in practice there will be a large number of slits and hence a large number of beamlets, which improves the efficiency of the isotope separation.

The scattering angle θ is also shown in Figure 1, as well as the angle θ_c which is the collimation angle. The scattering angle varies between θ_{min} to θ_{max} where

$$\theta_{min} = \frac{\theta_{max}}{\pi} \qquad (1)$$

The letter r indicates the distance between the point of origin of the beam Ø and one of the collimating slits while r′ indicates the distance between the same collimating slit to the collector 25.

It will be apparent that when a plurality of beamlets is generated using a single source they will not impinge normally upon the standing electromagnetic wave 16. In order to overcome this problem, the arrangement of Figure 2 may be utilized. Here the standing electromagnetic wave is arranged so that it extends along the circumference of a circle having its centre at the point of origin of the beam of particles. To this end, a plurality of prisms 35 may be introduced into the path of the standing electromagnetic wave 16. There may be as many as 20 prisms. This will ensure that all of the beamlets impinge substantially at right angles upon the standing electromagnetic wave front. This, in turn, makes it possible to utilize the entire beam emitted from the particle source 10. The distribution of the enriched or desired isotope is the same as in Figure 1. The arrangement of Figure 2 is particularly suitable for use with a beam of atoms.

The thickness, 1, of the standing electromagnetic wave, which the particle beam encounters, should be relatively small. This thickness may be calculated by the following formula:

$$1 < \frac{A_1^2}{A_2\phi}$$

A_1 is the wavlength of the standing electromagnetic wave,

A_2 is the wavelength of the particles, such as the atoms; and

ϕ is the phase shift of the particle wave moving across the crest of the electromagnetic wave.

In other words, ϕ measures the coupling between the particles and the electromagnetic field. Again, this relationship is particularly important to achieve the diffraction of atomic or molecular waves.

With reference to Figure 3, the particle source 10 is rather elongated to improve efficiency. The standing electromagnetic, in this case light, wave may, for example, be generated by one or more stacked lasers 40. The light emitted by the lasers 40 may be focussed by a pair of cylindrical lenses 41 and 42, lens 41 being biconvex while lens 42 is biconcave. The thus generated light beam 43 is reflected by a totally reflecting mirror 44 to generate the standing wave. It should be noted that the other mirror required for the formation of a standing wave is contained within the lasers 40. A plurality of baffles 45 may be disposed on a base 46 to form a plurality of slits 47.

By way of example the following values may be taken for dimensions of the apparatus of Figure 1: $Z = 2r = 20$ cm, where Z is the length of the standing electromagnetic wave. The distance $r + r' = 20$ cm and *b* may be 2.1×10^{-3} cm, (this is still an acceptable size for manufacturing, and results in a small energy expenditure per atom). The height of the atomic beam generated by the source 10 may be 10 cm or more. The thickness, 1, of the laser beam may be 5.4×10^{-2} cm.

In order to obtain such an extended light beam as shown in Figure 3, it may be desired to fold a laser beam back and forth upon itself. This has been shown in Figure 4, to which reference is now made. Figure 4 shows a laser 14 and a plurality of mirrors 50, 51, 50n, which are disposed above and below each other.

Each of the mirrors 50, 51, 50n, etc., consists of two inclined planes 52, 53, 52n, 53n, which reflect the original light beam 54 into a subsequent light beam 55 continually back and forth between the mirrors. The last mirror 56 is a plane totally reflecting mirror to return the light beam back to the laser 14. It will be understood that this arrangment may be used to provide the tall light beam 43 as shown in Figure 3.

It should be noted that the scattering or diffraction of the particles may be interfered with by the probability of collision between the particles. This effect, however, may readily be controlled by controlling the density of the particle beam and subsequent beamlets. It should also be noted that during a method according to the invention substantially no photons are consumed. That is, the internal energy state of the desired isotope is not changed; the isotope separation method is substantially eleastic.

It should be noted that there are major differences between atomic and molecular isotope separations using the present invention. In the first place, the photon scattering loss of the standing wave is significant for the atom but not for the molecule. Hence, there is a transparency constraint that applies to the atom but does not apply to the molecule. In order to minimize the absorptions of photons of light by the atomic particle beamlets, the light should have enough intensity to produce saturation of the atomic transition. It should also be noted that the standing light wave may have a frequency slightly off resonance, as long as it does not resonate with an undesired isotope.

The second difference has to do with the interaction time during the transition of the particles through the electromagnetic field. In the atom, the decay time from an upper level into states other than the ground state is short. Therefore, it determines the interaction time of the separation process. Thus, the thickness of the standing wave is commensurate with the distance travelled by an atomic particle during the lifetime of its excited state. This, however, is not true for the molecule, where we are concerned primarily with rotational or vibrational energy levels. Thus, for the molecule, the interaction may occur throughout the full transit time through the electromagnetic field. Since the thickness of the standing electromagnetic wave does not have to be restrained as in the case of the atom, it is the transit time of the molecule which determines the thickness.

In general, it will be necessary to cool the molecules so as to separate the transition lines of the two or more isotopes. In other words, this will reduce thermal line-broadening effects. For that reason a supersonic nozzle may be used. This may reduce the temperature to, say 55°K, and a carrier gas, such as xenon, may be used.

The last difference between atom and molecular beams is that it is not necessary to curve the path of the standing electromagnetic wave for a molecular beam. The reason is that the wavelength of the molecule is of the order of 16 micrometers, which is so long that the resonance line could not be doppler-shifted even if the beam does not impinge normal to the standing electromagnetic wave.

Since the desired or selected isotope is physically or spatially separated from the undesired isotope or isotopes, the physical separation may readily be effected. This may, for example, be effected by cutting out the collimated undesired isotopes from the space, say, between the regions defined by the curves 27—28 or 26—28. The remainder of the collector 25 should then carry primarily the desired isotope which may, for example, be removed by heating.

It should be noted that the separation method of the present invention may be used upon any desired element where the isotopes are to be separated.

A conventional separation may be that between the Uranium isotope 235 from isotope 238. In this case a separation may be carried out either on the atoms U or on the molecule UF_6, that is, uranium hexafluoride, or other uranium molecules.

Calculations have been made comparing the energy requirement per separated isotope and the product yield for the present invention and for other commercial and highly investigated processes. For a single pass of natural feedstock of Uranium, the energy requirement per separated atom for the process of the present invention is 76 keV. If the tailings of some other process is used having a 0.3 percent enrichment of U^{235}, to obtain a 3 percent enrichment the energy requirement is 120 keV. This compares to an energy requirement of 300 keV for the centrifugal process and of 3,000 keV for the gaseous diffusion process, both from natural feedstock. For the Jersey Nuclear-Arco Isotope process, the energy requirement starting with natural feedstock is 240 keV.

Thus, the energy requirement of the method of the present invention is substantially lower than other processes. In this connection, it should be specifically noted that the process of the present invention will also operate with the tailings of the feedstock of other processes. This permits the recovery of more U^{235}, which would normally be considered a waste product.

The product yield in grammes per second of reactor grade Uranium for the method of the present invention using natural feedstock is 3.3×10^{-3} and for the tailings as feedstock having a 0.3 percent assay, the yield should be 7.2×10^{-4} for a single pass. Published figures for the centrifugal process show a product yield of 5×10^{-5}.

The method of the present invention is relatively simple and does not require a large apparatus. Hence, it could be easily used for processing small amounts of material. The method works for both atoms and molecules, while prior processes operate for either atoms only, or for molecules only. It has been shown that the energy requirement per separated isotope is less than that of other known processes and the product yield per separating unit is greater. In particular, it makes it possible to utilize the waste feedstock from other processes to bring the amount of U^{235} from 0.3 percent enrichment or even lower, to 3 percent enrichment.

CLAIMS

1. Apparatus for separating isotopes, comprising:
(a) means for generating a beam of particles having a desired and at least one other isotope;
(b) means for collimating the beam of particles into a plurality of beamlets;
(c) means for generating a standing electromagnetic wave, extending transverse the path of the particles, the said electromagnetic wave having a frequency substantially corresponding to an internal excitation level of the desired one of the isotopes, thereby to scatter particles of the desired isotope without substantially exciting the particles after scattering; and
(d) means for collecting the scattered particles, the particles forming substantially separated intensity peaks, substantially in the plane defined by the particle beam and the electromagnetic wave.

2. Apparatus as claimed in Claim 1, wherein the standing electromagnetic wave extends substantially normal to the path of the beamlets.

3. Apparatus as claimed in Claim 1 or 2, wherein said means for generating a beam of particles comprises a source including an oven.

4. Apparatus as claimed in Claim 1 or 2, wherein said means for generating a beam of particles comprises a source including a supersonic nozzle.

5. Apparatus as claimed in Claim 1, 2 or Claim 3, wherein said particles are atoms.

6. Apparatus as claimed in Claim 1, 2 or 4, wherein said particles are molecules.

7. Apparatus as claimed in any preceding claim, wherein means are provided for curving the said standing electromagnetic wave about the circumference of a circle having its centre substantially at a point of origin of the beam of particles, thereby to cause the beamlets to impinge upon the said standing electromagnetic wave substantially at right angles.

8. Apparatus as claimed in Claim 7, wherein said means for curving comprises a plurality of prisms interposed in the path of the standing electromagnetic wave.

9. Apparatus as claimed in Claim 5 or either of Claims 7 and 8 as dependant on Claim 5, wherein the thickness of the electromagnetic wave is commensurate with the distance travelled by an atomic particle during its excited state lifetime.

10. Apparatus as claimed in Claim 6, wherein the said standing electromagnetic wave has a height comparable to the length of the particle beam and is disposed substantially normal to the particle beam.

11. Apparatus as claimed in any preceding claim, wherein said means for generating a standing electromagnetic wave includes a laser and a plurality of mirrors so disposed as to reflect the standing electromagnetic wave back and forth to obtain a wave having a substantial height.

12. Apparatus as claimed in Claim 6, Claim 10 or Claims 6 and 11, wherein the thickness of the electromagnetic wave is less than substantially

$$\frac{A_1^2}{A_2 \emptyset}$$

where A_1 is the wavelength of said electromagnetic wave, A_2 is the wavelength of the molecular particles and $\emptyset$ is the phase shift of the molecular wave across a crest of said electromagnetic wave.

13. A method of separating isotopes comprising the steps of:
(a) generating a beam of particles including a desired and at least one other isotope;
(b) collimating the beam of particles into a plurality of beamlets;
(c) generating a standing alectromagnetic wave extending transverse the path of the particle beam and having a frequency substantially corresponding to an internal excitation level of the desired one of the isotopes, thereby to scatter particles of the desired isotope and to spatially separate the desired isotopes from other isotopes into separate intensity peaks substantially in the plane defined by the particle beam and the electromagnetic wave; and
(d) collecting the scattered particles.

14. A method as claimed in Claim 13, wherein the standing electromagnetic wave extends substanitally normal to the path of the beamlets.

15. A method as claimed in Claim 13 or 14, wherein said beam of particles consists of atoms.

16. A method as claimed in Claim 13 or 14, wherein said beam of particles consists of molecules.

17. A method as claimed in any of Claims 13 to 16, wherein the standing electromagnetic wave is curved to form a portion of a circle having its centre substantially at a point of origin of the beam of particles, whereby the beamlets impinge upon the standing electromagnetic wave substantially at right angles.

18. A method as claimed in Claim 15 or Claims 15 and 17, wherein the thickness of the electromagnetic wave is commensurate with the distance travelled by an atomic particle during its excited state lifetime.

19. A method as claimed in Claim 16, wherein the standing electromagnetic wave has a height comparable to the length of the particle beam and is disposed substantially normal to the path of the beam of particles.

20. A method as claimed in any of Claims 13 to 19, wherein the standing electromagnetic wave is a monochromatic wave.

21. A method as claimed in Claim 16 or Claim 19 when appendant to Claim 16, wherein the thickness of the electromagnetic wave is less than substantially

$$\frac{A_1^2}{A_2 \emptyset}$$

where A_1 is the wavelength of said wave, A_2 is the wavelength of the molecular particles and $\emptyset$ is the phase shift of the molecular wave across a crest of said wave.

22. An apparatus for separating isotopes, substantially as hereinbefore described with reference to the accompanying drawings.

23. A method for separating isotopes substantially as hereinbefore described with reference to the accompanying drawings.

Printed for Her Majesty's Stationery Office, by Croydon Printing Company Limited, Croydon, Surrey, 1984.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.