# United States Patent

**Kaminsky**

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[54] **METHOD FOR PRODUCING A BEAM OF POLARIZED ATOMS**


[72] Inventor: **Manfred S. Kaminsky**, Hinsdale, Ill.

[73] Assignee: **The United States of America as represented by the United States Atomic Energy Commission**



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[52] **U.S. Cl.** .....**250/84,** 250/86, 250/105

[51] **Int. Cl.**.....**G21k 1/00**

[58] **Field of Search** ..250/84, 86, 225, 105; 350/151; 313/112, 84, 87



[56] **References Cited**

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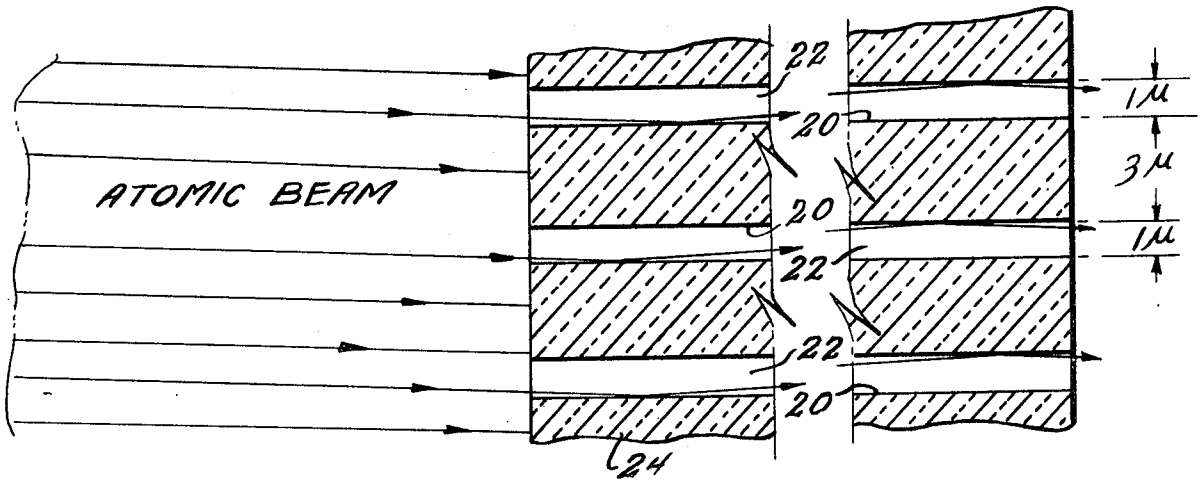
*Primary Examiner*—James W. Lawrence
*Assistant Examiner*—Harold A. Dixon
*Attorney*—Roland A. Anderson



[57] **ABSTRACT**

A polarized beam of atoms is generated by forming a plurality of apertures of micron-sized diameter through a magnetically saturated monocrystalline material and passing in a partial vacuum a collimated beam of atoms through said apertures incident to the walls thereof. The monocrystalline material effects a charge-transfer reaction with the atomic beam to produce a polarized beam of atoms, the nuclei of which are subsequently polarized by hyperfine interaction in a weak external magnetic field.


**11 Claims, 5 Drawing Figures**



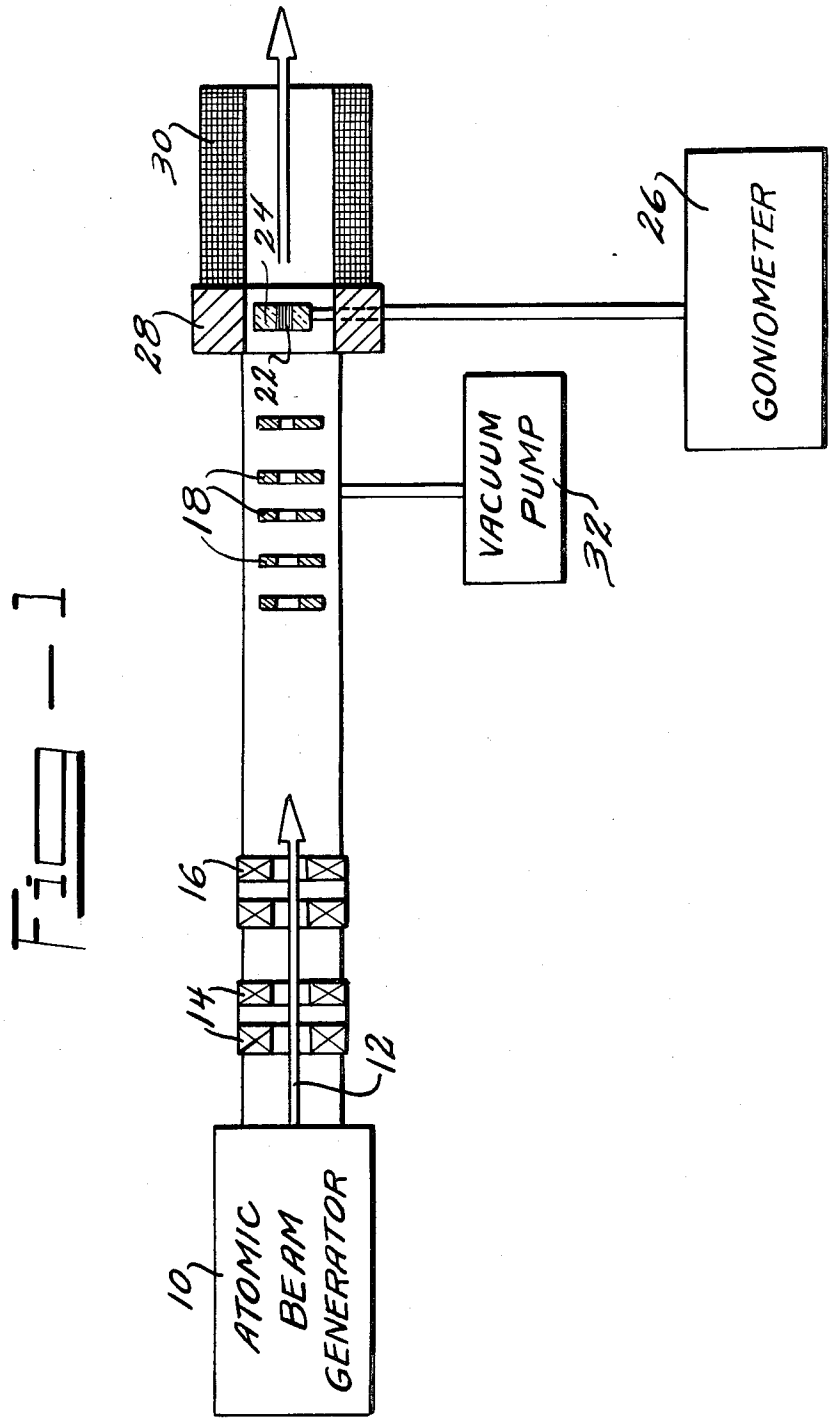
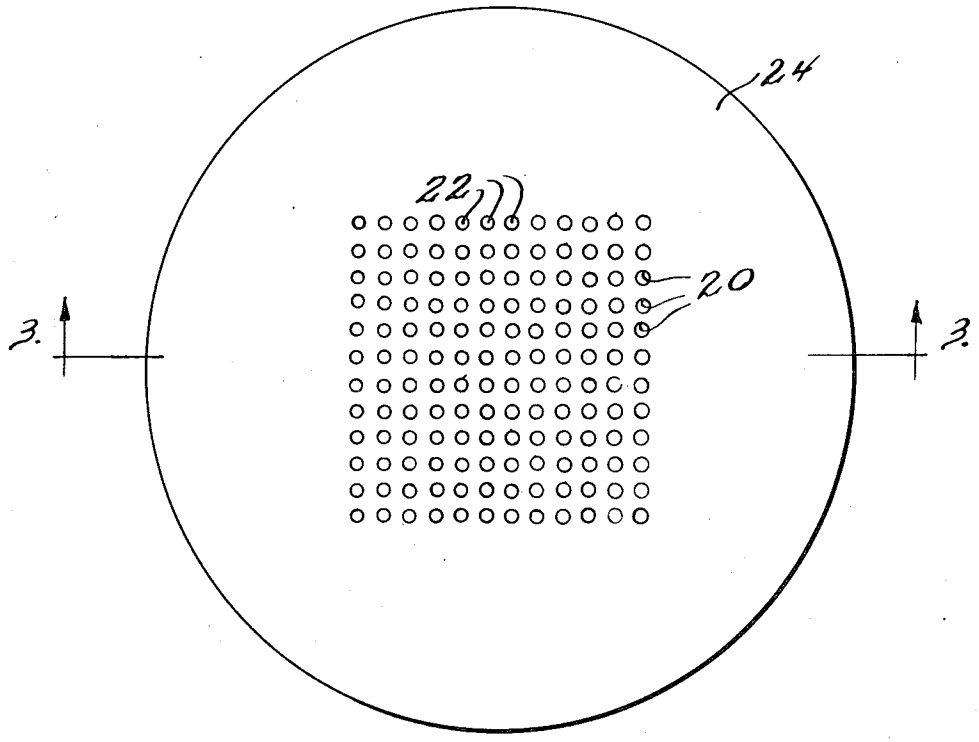
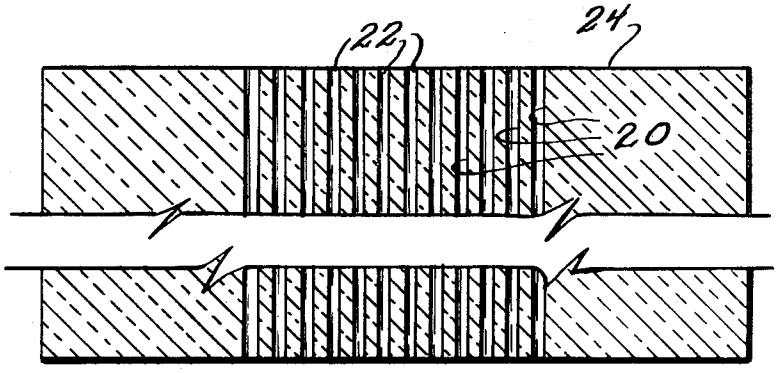

30
24
26
GONIOMETER
28
22
VACUUM PUMP
32
18
16
14
12
10
ATOMIC BEAM GENERATOR

Fig. 1

Fig—2




Fig—3



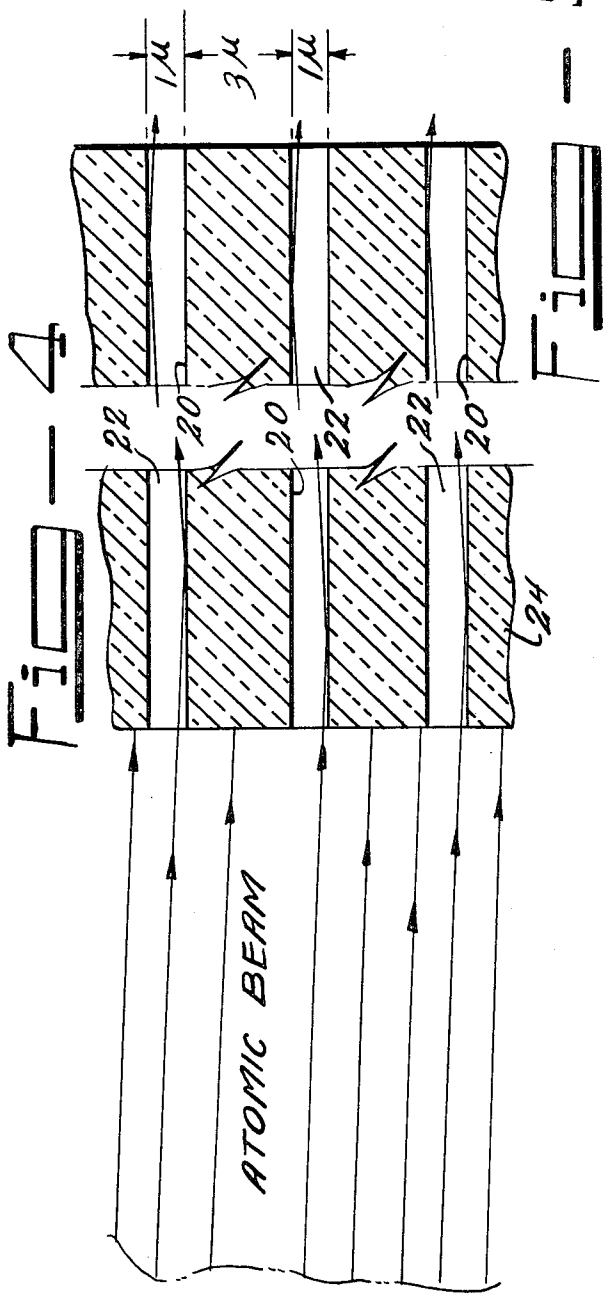

1μ
3μ
1μ
22
20
20
22
22
20
24
ATOMIC BEAM

Fig. 4

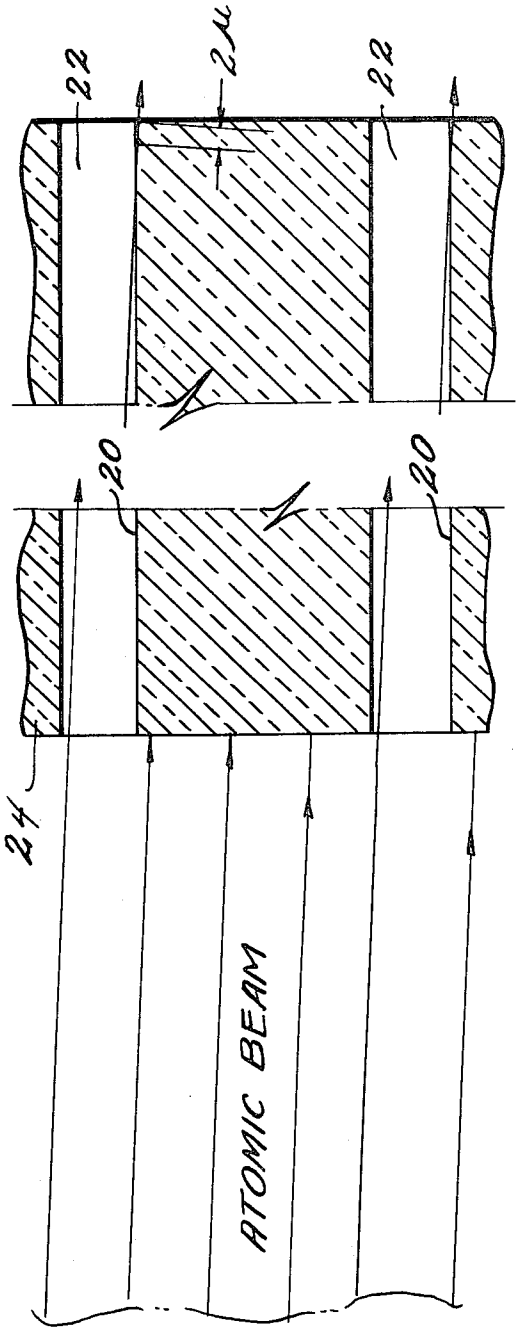

22
2μ
22
20
20
24
ATOMIC BEAM

Fig. 5

# METHOD FOR PRODUCING A BEAM OF POLARIZED ATOMS

## CONTRACTUAL ORIGIN OF THE INVENTION

The invention described herein was made in the course, or under, a contract with the UNITED STATES ATOMIC ENERGY COMMISSION.

## BACKGROUND OF THE INVENTION

This invention relates to methods for producing polarized atomic beams.

Polarized atoms are generally used in particle accelerators to study nuclear reactions. Presently, polarized atoms are produced by an atomic beam method using separation magnets and rf transitions, as disclosed by W. Haeberli, "Sources of Polarized Ions," Annual Review of Nuclear Science, Vol. 17, 1967. This polarized method of producing atoms is expensive and also requires relatively complex equipment. In my U. S. Pat. No. 3,569,705 entitled "Method for Producing Polarized Atoms," Mar. 9, 1971, I disclosed a method for generating polarized atoms by passing a collimated atomic beam through a magnetically saturated monocrystalline material parallel to a lattice channel of the material. The monocrystalline material effects a charge-transfer reaction with the atomic beam to produce a polarized atomic beam, the nuclei of which are subsequently polarized by hyperfine interaction in a weak external magnetic dipole field. The present invention is an improvement over that disclosed in my aforedescribed patent.

It is one object of the present invention to provide an improved method and means for producing polarized atoms.

It is another object of the present invention to provide a relatively inexpensive method and means for producing polarized atoms.

It is still another object of the present invention to provide a method and means for producing a polarized atomic beam of variable intensity.

It is another object of the present invention to provide a method and means for effecting a variable charge-transfer reaction between a magnetically saturated monocrystalline material and an atomic beam.

Other objects of the present invention will become more apparent as the detailed description proceeds.

## SUMMARY OF THE INVENTION

A beam of atoms is polarized according to the present invention by generating a plurality of apertures of micron-sized diameter through a magnetically saturated monocrystalline material and passing, in a partial vacuum, a collimated beam of atoms through the apertures incident to the walls thereof, the monocrystalline material polarizing the atomic beam to provide a beam of polarized atoms.

## BRIEF DESCRIPTION OF THE DRAWINGS

Further understanding of the present invention may best be obtained from consideration of the accompanying drawings wherein:

FIG. 1 is a schematic diagram of an apparatus for the practice of the present invention;

FIG. 2 is a front view of a monocrystalline material used in the apparatus of FIG. 1.



FIG. 3 is a cross sectional view of the monocrystalline material of FIG. 2 taken along lines 3—3.

FIG. 4 is an enlarged cross sectional view of a monocrystalline material used in the apparatus of FIG. 1 illustrating the scattering mode of operation in the practice of the present invention;

FIG. 5 is an enlarged cross sectional view of a monocrystalline material used in the apparatus of FIG. 1 illustrating the penetration made in the practice of the present invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

In the practice of the present invention a plurality of apertures of micron-sized diameter are formed through a magnetically saturated monocrystalline material in a direction parallel to a lattice channel in the material. A beam of atoms (positive ions, negative ions or neutral atoms) is generated and highly collimated to pass through the apertures in the material and impinge on the interior walls thereof. The atomic beam, in passing through the apertures of the magnetically saturated monocrystalline material and striking the interior walls thereof, undergoes a charge-transfer reaction with the material to capture polarized electrons whereby the beam emerging from the monocrystalline material is a beam of polarized atoms. Subsequent to passage through the monocrystalline material, the beam is passed adiabatically into a weak magnetic field having the same directional sense as the direction of the field of magnetization of the monocrystalline material. This weak magnetic field extends in the direction of transmission of the atomic beam a distance sufficient to provide a transit time for the atomic beam greater than the Lamor precession time of the nuclear magnetic moment of the nuclei of the atomic beam thereby effecting nuclear polarization of the beam by hyperfine interaction. Thus, in the weak magnetic field, nuclear polarization by hyperfine interaction between the magnetic moment of a captured polarized electron and the nuclear magnetic moment of the associated nucleus of the atom is effected.

For the practice of the present invention, a lattice channel in the monocrystalline material includes the planar channels and axial channels of the material as exemplified by the [110], [100], [111], or [112] axial channels and (110), (100), (111), or (112) planar channels of a face centered cubic monocrystalline material. It will be appreciated that similar channels exist for other monocrystalline materials having different crystallographic structure such as body centered or hexagonal close-packed materials and the present invention is equally applicable thereto.

A specific apparatus for the practice of the present invention is illustrated in FIGS. 1–3. A beam generator 10 generates a beam of atoms 12 which is passed through a pair of quadrupole magnets 14 and 16. Subsequent to the quadrupole magnets 14 and 16, the beam 12 is passed through the successively diameterically decreasing apertures of collimators 18 to impinge on the interior walls 20 of like apertures 22 extending through a ferromagnetic monocrystalline material 24. The apertures 22 are of micron-sized diameter and are formed in the material 24 so as to be parallel to a lattice channel of the material 24 as hereinbefore described.

The monocrystalline material **24** is mounted on a goniometer **26** to enable adjustable motion of the material to align the apertures therethrough relative to the generated beam **12**. A magnet **28** provides a DC magnetic field through the monocrystalline material **24** normal to the direction of the longitudinal axis of the apertures sufficient to effect magnetic saturation of the material **24**. The beam **12** passes adiabatically from the strong magnetic field region of apertures **22** into a weak magnetic field region generated by a second magnet **30**. The magnet **30** is mounted to provide a weak homogeneous magnetic dipole field in the same directional sense as the direction of the field of magnetization passing through the monocrystalline material **24**.

The aforedescribed structure is housed so that the beam generation and transmission through the collimator **18** and monocrystalline material **24** and the magnetic field from magnet **30** is accomplished in a high vacuum maintained by a vacuum pump **32** at approximately $10^{-6}$ Torr or higher.

The apertures **22** extending through the monocrystalline material **24** are more clearly illustrated in FIGS. **2** and **3**. As previously stated, the apertures **22** are equal and micron-sized in their diameter. For the practice of the present invention, it is preferred that the diameter of the apertures **22** be between 0.1 micron and 1.0 micron. Further, it is preferred that the ratio of the diameter of each aperture **22** to length of the aperture **22** be between 1/500 to 1/5,000. Thus, where the diameter of the apertures **22** is 0.1 microns the length of the aperture is from 50 to 500 microns and where the diameter of the aperture **22** is 1 micron then it is preferred that the length of the aperture be from 500 to 5,000 microns. In the cross sectional array of the apertures **22** in the monocrystalline material **24**, it is preferred for the practice of the present invention that the distance on center between the apertures **22** be approximately 4 times the diameter of the aperture **22**.

It is to be noted that, though the example in FIGS. **2** and **3** shows a sectional array of the apertures **22** as being rectangular, the present invention is not limited thereto. Other arrays may be used, for example, circular. For the practice of the present invention, the sectional array of apertures **22** should be such that the array be larger than the cross section of the particle beam **12**.

The apertures **22** may be formed in the monocrystalline material **24** by conventional electron beam drilling or photo-etching. For the present invention, it is preferred that after the electron beam drilling or photoetching the walls of apertures **22** be etched or electro-polished to remove therefrom a radial thickness of 200 A whereby lattice damage to the crystal material **24** from the electron beam drilling is removed and polishing of the walls of the apertures **22** is effected.

In operation, the beam **12** emerging from the generator **10** is acted upon by the quadrupole field of magnets **14** and **16** to reduce the beam diameter. The apertures in the collimator **18** are aligned in decreasing size arrangement to provide a highly collimated beam **12** of approximately 1 millimeter diameter at the surface of the monocrystalline material **24**. The monocrystalline material **24** is adjusted on its goniometer mount **26** so that the apertures **22** are aligned relative to the highly collimated beam **12** to effect incidence of the beam **12** on the interior walls **20** of the apertures **22** as the beam traverse the apertures. Thus, the atoms in the beam **12** collide with the interior walls **20** of the apertures **22** as they traverse the apertures. With the monocrystalline material **24** in a state of magnetic saturation, the collimated beam **12** passing through the apertures **22** in collisional relationship therewith captures polarized electrons from the material **24** in a charge-transfer reaction to provide an emerging atomic beam which is polarized. From the strong magnetic field region of the apertures **22**, the beam **12** passes adiabatically into the weak homogeneous magnetic dipole field generated by magnet **30** in the same directional sense as the direction of the field of magnetization from magnet **28** whereby the axis of polarization is kept unperturbed and nuclear polarization by hyperfine interaction between the magnetic moment of the captured polarized electron from the material **24** and the nuclear magnetic moment of the atom in the beam **12** is effected. It will be appreciated that, for this nuclear polarization by hyperfine interaction, the transit time for the atomic beam in the weak magnetic dipole field from magnet **30** is greater than the Lamor precession time of the nuclear magnetic moment of the nuclei of the atomic beam. Thus, at the output of the weak magnetic dipole field generated by the magnet **30** a beam of nuclear-polarized atoms is produced.

It will be appreciated that the beam **12** must be generated having sufficient energies to effect the desired charge-transfer reaction with the monocrystalline material. Typical beam energies emerging from the monocrystalline material **24** are approximately 60,000 electron volts for deuterium atoms and 30,000 electron volts for hydrogen atoms. Further, magnetic saturation of the material **24** has been found satisfactory with an initial magnetic field from magnet **28** of 12 kilogauss and a final saturation maintaining field of 160 gauss. A satisfactory weak field generated by magnet **30** is approximately 10 gauss.

The apparatus of FIGS. **1–3** provides two modes of operation. The first mode, herein called the scattering mode, is effected by adjusting the goniometer **26** so that the apertures **22** through the monocrystalline material **24** are aligned relative the highly collimated beam **12** to cause the beam to undergo a series of glancing collisions with the interior walls **20** of the apertures **22** as the beam traverses the apertures. This mode is illustrated in FIG. **4**. Thus, in the scattering mode, the atoms in the beam **12** undergo a series of glancing collisions with the interior walls **20** of the apertures **22** as they traverse the apertures whereby the atoms capture polarized electrons from the material **24** in a charge-transfer reaction. To effect this method the highly collimated beam **12** should have an angle of incidence relative to the walls **20** of apertures **22** of approximately 89°. As the angle of incidence of the beam **12** relative to the walls **20** decreases, the intensity (i.e., number of polarized particles in the beam) of the polarized beam output from the monocrystalline material **24** decreases. This results because a larger percentage of the beam penetrates the material **24** and is lost. As the angle of incidence of the beam **12** relative the interior walls **20** increases from 89°, the intensity of the polarized beam output will increase provided the

apertures 22 are long enough to enable a sufficient number of collisions between the atoms and the interior walls 22. The aforedescribed aperture diameter to length ratios enable such a sufficient number of collisions to be effected. This effect is observed until the beam 12 is parallel to the apertures 22 at which point no interaction between the beam and the material 24 takes place and no polarized electrons are captured therefrom whereby polarization drops to zero. Thus, in the scattering mode, the maximum interaction by particles in the beam 12 with the interior surface 20 is achieved with a relative angle of incidence therebetween greater than 89° and less than 90°. It is to be noted that the intensity of the polarized output beam may be varied by varying the angle of incidence between the beam 12 and the walls 20.

The second mode of operation, herein called the penetration mode, is effected by adjusting the goniometer 26 to align the apertures 22 relative to the highly collimated beam 12 so that the beam is incident on the wall 20 only once and passes through the material 24 to exit therefrom as a polarized beam. This mode is illustrated in FIG. 5. The angle of incidence of the beam 12 relative to the interior wall 20 for the penetration mode is such that the atoms in the beam 12 traverse less than 0.2 microns of the material 24. Where the angle of incidence of the beam 12 relative the interior walls 20 is such that the atoms in the beam are caused to travel more than 0.2 microns through the monocrystalline material 24, the intensity of polarization of the output beam drops, since a larger percentage of the beam is trapped by the material. It is to be noted that the intensity of the polarized output beam may be varied by varying the angle of incidence between the beam 12 and the walls 20 whereby the distance of the material 24 traversed by the atoms in the beam 12 is varied. The maximum intensity is achieved with the shortest distance travelled by the atoms through the material 24, that is less than 0.2 microns and greater than zero. Energy discrimination may be used on the beam after passage through the weak magnetic field of magnet 30 by passing the beam through a Wien filter to effect an output beam of atoms whose energies are characterized by having passed through the monocrystalline material 35 a distance greater than zero and less than 0.2 microns.

Both of the modes, hereinbefore described, provide for the present invention a polarizing effect which is comparable to having a monocrystalline material of variable thickness. That is, a polarized output beam of variable intensity may be readily produced.

It will be appreciated that the present invention may be utilized with atomic beams to produce nuclear-polarized atoms which are either neutral, negative, or positive. For example, where positive hydrogen atoms are generated to impinge on the interior wall 20 of apertures 22, polarized neutral hydrogen atoms are produced at the output of the magnetic field of magnet 30. Transfer of the polarized neutral hydrogen atoms to positive or negative polarized hydrogen atoms may then be effected by passing the beam through a lattice channel of a monocrystalline charge-transfer foil. The present invention is applicable to atomic beams of atoms having low atomic numbers such as protons, deuterons, tritons, and helium, and may be used to produce polarized atoms of these substances. The present invention may also be applied to atoms having higher atomic numbers, such as lithium-6, lithium-7, boron-11 and fluorine-19, and may be used to produce polarized atoms of these substances.

For maximum polarization according to the present invention, the atomic beam 12 should be collimated so that it has a maximum half-angle of divergence of 0.01° at a low index plane of the monocrystalline material 24. As the angular divergence of the beam 12 increases, the efficiency of the present invention falls off. The present invention is effective only with monocrystalline materials, While as previously set forth, the present invention operates satisfactorily with any ferromagnetic monocrystalline material, the invention should also operate satisfactorily with paramagnetic monocrystalline materials having a high magnetic susceptability, that is, paramagnetic monocrystalline materials having a Heisenberg's exchange integral ratio of the average lattice distance to the lattice atom diameter greater than 1.5. This includes such monocrystalline paramagnetic materials as gadolinium, dysprosium, holmium and terbium.

Persons skilled in the art will, of course, readily adapt the general teachings of the invention to embodiments far different from the embodiments illustrated. Accordingly, the scope of protection afforded the invention should not be limited to the particular embodiment illustrated in the drawings and described above but should be determined only in accordance with the appended claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method of polarizing a beam of atoms comprising generating an aperture through a monocrystalline material parallel to a lattice channel in said material, magnetically saturating said monocrystalline material in a direction normal to the longitudinal axis of said aperture, generating a partial vacuum, and transmitting in said partial vacuum said beam of atoms through said aperture to be incident on the interior wall thereof and effect a charge-transfer reaction therewith to polarize said beam.

2. The method according to claim 1 wherein said atomic beam is collimated to provide a maximum half-angle of divergence from the axis of transmission of said beam at the surface of said monocrystalline material of 0.01°.

3. The method according to claim 1 wherein said atomic beam is transmitted to impinge on the interior surface of said aperture at an incident angle with respect thereto greater than 89° and less than 90°.

4. The method according to claim 1 wherein said aperture is generated having an aperture diameter to length ratio between 1/500 and 1/5,000 and having a diameter between 0.1 micron and 1.0 micron.

5. The method according to claim 1 wherein said atomic beam is transmitted through said aperture to be incident on the interior wall thereof and pass through said monocrystalline material a distance less than 0.2 microns.

6. The method according to claim 1 further including generating a magnetic field, and transmitting said atomic beam adiabatically from said magnetically satu-

rated monocrystalline material through said magnetic field a distance in the direction of transmission of said atomic beam sufficient to provide a transit time therefor greater than the Lamor precession time of the nuclear magnetic moment of the nuclei of the atomic beam to effect nuclear polarization of said beam by hyperfine interaction.

7. The method according to claim 6 wherein said magnetic field is generated in the same directional sense as the magnetic saturation of said monocrystalline material.

8. The method according to claim 6 wherein said beam of atoms is transmitted through said aperture to engage the interior wall thereof adjacent the beam exit side of said monocrystalline material and pass through said monocrystalline material a distance to effect a charge transfer therewith and polarize said beam.

9. A method of polarizing a beam of atoms comprising forming an aperture through a monocrystalline material parallel to a lattice channel therein, magnetically saturating said monocrystalline material in a direction normal to said aperture, collimating said beam of atoms to provide a maximum half angle of divergence from the axis of transmission of said beam at the surface of said monocrystalline material of 0.01°, generating a partial vacuum, transmitting said collimated beam in said partial vacuum through said aperture to interact with the interior wall thereof and effect a charge-transfer reaction therewith the polarize said beam.

10. The method according to claim 9 wherein said aperture has a diameter greater than 0.1 micron and less than 1.0 micron and a diameter to length ratio greater than 1/5,000 and less than 1/500, and said beam is transmitted through said aperture to impinge on the interior surface thereof with an incident angle thereto greater than 89° and effect a charge-transfer polarization of said beam.

11. The method according to claim 9 wherein said beam is transmitted to pass through said monocrystalline material a distance less than 0.2 microns while traversing said aperture to effect a charge-transfer polarization of said beam.

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