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ATOMIC BEAM TUBE HAVING MULTIPOLE STATE SELECTING MAGNET MEANS WITH SHAPED POLES TO INHIBIT MAJORANA TRANSITIONS

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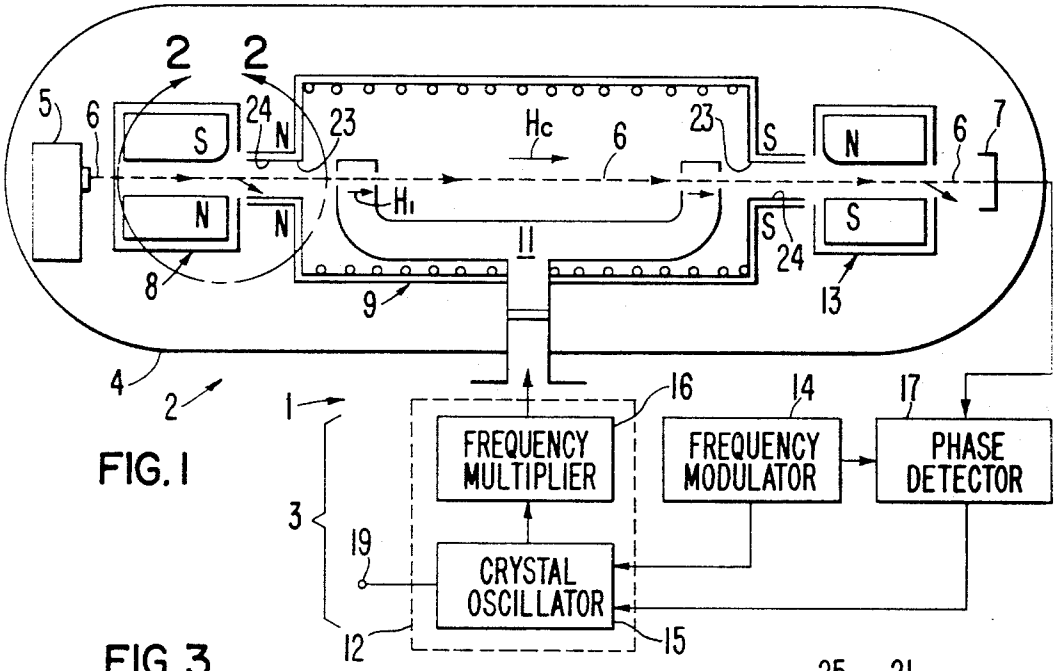


FIG. 1

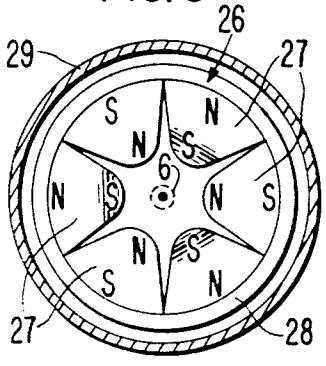


FIG. 3

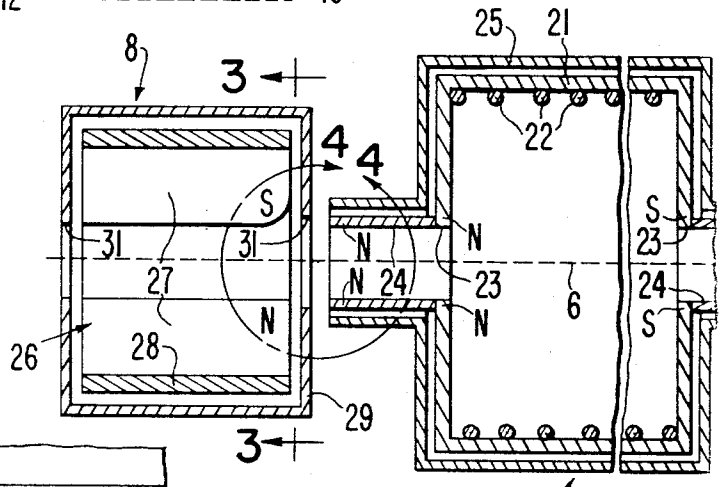


FIG. 2

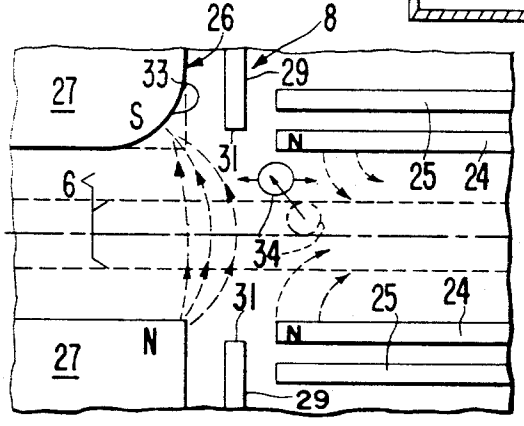


FIG. 4

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ATOMIC BEAM TUBE HAVING MULTIPOLE STATE SELECTING MAGNET MEANS WITH SHAPED POLES TO INHIBIT MAJORANA TRANSITIONS

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ABSTRACT OF THE DISCLOSURE

An atomic beam tube having multipole state selecting magnets configured to prevent an abrupt field reversal between the state selecting magnets and the adjacent C-field region, and thus to prevent undesirable Majorana transitions in the atoms of a beam. The poles of each state selecting magnet which have the same polarity as the adjacent C-field are rectangular in cross section, and the other poles which have a polarity opposite to that of the adjacent C-field are tapered in cross section.

The present invention relates in general to atomic beam tubes and, more particularly, to an improved beam tube of the type using multipole energy state selecting magnets and wherein certain of the poles of the energy state selecting magnets are shaped to inhibit Majorana transitions, whereby the accuracy of the resonance frequency of the atomic beam tube is improved. Such improved atomic beam tubes are useful for example, as the reference frequency for frequency standards or atomic clocks.

Heretofore, atomic beam tubes have been built using both cesium and thallium atoms wherein a beam of atoms passed from a source axially through a hexapole energy state selecting magnet into a weak axially directed C-field and thence through a second hexapole magnet into a beam detector. Typically a magnetically shielded solenoid is used, in tubes employing multipole state selecting magnets, to generate the weak uniform magnetic field as of 20 milligauss of the C-field region within which field independent hyperfine transitions of the atoms making up the beam are induced at the certain microwave resonance frequency by application of a microwave magnetic field at the field independent hyperfine resonance frequency.

It turns out that if the atomic beam traverses an abrupt change in direction of the magnetic field at low magnetic field intensities on the order of C-field intensity such as found in the regions of space between the C-field and the state selecting magnetic fields then there is a strong possibility that Majorana transitions will be induced from certain of the higher hyperfine energy states to certain lower Zeeman sublevels of that upper hyperfine energy state. The result is a change in the symmetry of the field independent hyperfine resonance line shape which produces a minute apparent shift in the center resonance frequency of the detected field independent hyperfine resonance frequency, thereby producing an error in the reference frequency of the atomic frequency standard or atomic clock using the atomic beam tube.

It has been found that with the typical prior art geometry of a shielded multipole state selecting magnet disposed adjacent a shielded C-field solenoid that a region of weak magnetic field, on the order of C-field intensity, is produced on the axis of the beam path which region of weak field is also accompanied by an abrupt change in the direction of the magnetic field, thereby producing undesired Majorana transitions of the atoms in the beam.

In the present invention, the shape of the pole structure

of the conventional multipole state selecting magnet is altered by removing portions of either the north poles or the south poles which face the opposite pole of the C-field solenoid such as to move the region of weak field out of the beam path and, thus, inhibit undesired Majorana transitions. In this manner, the Majorana caused minute error in the reference frequency of the atomic beam tube is prevented.

The principal object of the present invention is to provide an improved atomic beam tube.

One feature of the present invention is the provision of a multipole state selecting magnet having portions of its magnetic poles which face the C-field magnetic pole of opposite polarity spaced a greater distance from the C-field pole than the remaining poles of the state selecting magnet which have the same polarity as the adjacent C-field pole, whereby Majorana transitions of the atomic beam are inhibited in use.

Another feature of the present invention is the same as the preceding feature wherein the state selecting magnet is either a quadrupole or hexapole magnet.

Another feature of the present invention is the same as any one or more of the preceding wherein the C-field magnet is a magnetically shielded solenoid coaxially aligned with the state selecting magnet.

Other features and advantages of the present invention will become apparent upon a perusal of the following specification taken in connection with the accompanying drawings wherein:

FIG. 1 is a longitudinal schematic view, partly in block diagram form, of a frequency standard employing features of the present invention,

FIG. 2 is an enlarged view of a portion of the structure of FIG. 1 delineated by line 2—2,

FIG. 3 is a cross sectional view of the structure of FIG. 2 taken along line 3—3 in the direction of the arrows, and

FIG. 4 is a enlarged schematic diagram of that portion of FIG. 3 delineated by line 4—4 depicting the magnetic field lines.

Referring now to FIG. 1 there is shown a typical atomic beam tube frequency standard **1** employing the features of the present invention. More particularly, the frequency standard **1** includes an atomic beam tube **2** together with its associated circuitry **3**. The tube **2** includes a hollow vacuum envelope **4** as of stainless steel evacuated to a low pressure as of 10^{-7} torr. via a pump, not shown. An oven source **5** provides a source of atomic beam material as, for example, atomic Cs or Tl which it projects into an elongated beam path **6** to a detector **7** at the opposite end of the tube **2**.

A first shielded multipole energy state selecting magnet assembly **8** receives the beam. The beam passes axially through the selector magnet **8** which serves to focus or deflect out of the beam path **6** those atoms of the beam which are not in a certain selected upper energy state. The selected atoms of the beam then pass into a shielded C-field magnet assembly **9** which produces a C-field region therein of a relatively uniform and weak field H_c, as of 20 milligauss, which is axially directed parallel to the beam path **6**.

A split field C-field cavity resonator **11** is resonant at the field independent hyperfine resonance frequency of the atoms of the beam **6** and is excited with microwave energy at this frequency as derived from a microwave signal generator portion **12** of the circuitry **3**. The split field cavity resonator **11** may comprise, for example, a Y-shaped section of H-bend rectangular waveguide shorted at the ends of the two arm portions of the Y and apertured adjacent the shorted ends to permit passage of the beam **6** through regions of alternating magnetic field H_1,

directed parallel to the C-field H_c and at the hyperfine resonant frequency to excite resonance of the beam.

A second magnetically shielded multipole energy state selecting magnet assembly **13** is disposed coaxially of the beam, as with magnet assembly **8**, and is disposed inbetween the C-field magnet **9** and the beam detector **7**. The second state selecting magnet **13** serves to focus or deflect out of the beam those atoms in the lower energy states and to retain in the beam atoms in the certain higher energy states.

In operation, the first multipole state selecting magnet deflects out of the beam the lower energy state atoms. A modulator **14** modulates a crystal oscillator frequency source **15** in the microwave generator **12**. The modulated frequency is multiplied by a frequency multiplier portion **16** of the microwave generator **12** to produce a frequency modulated output at the field independent hyperfine resonance frequency which is used to excite resonance of the beam in the C-field cavity **11**. At resonance, transistions of the atoms of the beam from the upper selected hyperfine energy state to a lower hyperfine energy state is produced. However this resonance is modulated due to the impressed frequency modulation.

The second multipole state selecting magnet **13** deflects out of the beam those atoms in the lower hyperfine energy states and, thus, those atoms which have undergone a hyperfine transition in the C-field cavity **11**. As a result, the detected signal at detector **7** is modulated at the modulation frequency of the modulator **14** as, for example, 10s of Hz. The modulated resonance signal is phase sensitive detected against the modulation frequency from modulator **14** in phase sensitive detector **17** to produce a D.C. error signal which is fed to the crystal oscillator **15** to tune the microwave generator **12** to precisely the center frequency of the hyperfine resonance. An output, at a convenient frequency as of 5 mHz., is extracted from the crystal oscillator at terminal **19** and serves as the reference frequency output of the frequency standard **1**.

Referring now to FIGS. 1–4 the C-field magnet **9** includes a cylindrical substantially closed magnetically permeable shell **21** as of iron forming the flux return path for a solenoid **22** wound on the inside of the shell **21** to form the C-field magnet. The magnet is coaxial with the beam path **6** and includes a pair of apertures **23** in the end walls of the cylindrical yoke **21** and on the beam axis. A pair of tubular magnetically permeable tubes **24** extend axially away from the C-field magnet yoke **21** toward the adjacent state selecting magnet assemblies **8** and **13**, respectively, and form part of the pole structure of the C-field magnet **21**.

A cylindrical magnetically permeable shell **25** as of Permalloy, is spaced outwardly from the magnet **21** and envelopes same to form a magnetic shield. The shield **25** has the same geometrical configuration as the yoke **21**.

The multipole magnet structures **8** and **13** each include a multipole magnet **26** having an even number of and at least four permanent magnets **27** inwardly projecting from a cylindrical yoke **28**, as of iron. Adjacent magnets **27**, as taken around the beam path **6** axially passing therethrough, are oppositely radially polarized to form alternating polarity poles facing the beam path **6**. A hexapole magnet **26** is depicted, however, quadrupole magnets or magnets having 8, 10—etc. poles may be used. A cylindrical magnetically permeable shield **29**, as of Permalloy, envelopes each of the multipole state selecting magnets **26**. A pair of beam apertures **31** are provided on the beam path **6** in the end walls of the shields **29** for passage of the beam therethrough.

It has been found that in the prior art design, wherein the spacing from the pole pieces to the beam axis **6** was uniform over the axial length of the multipole magnet that undesired Majorana transitions were being induced in the upper hyperfine energy state. These transitions are undesired as they distort the shape of the spectrum of the output resonance signal and introduce slight errors in the controlled reference output frequency at terminal **19**.

These Majorana transitions were being caused by the beam atoms passing through a relatively weak magnetic field **34**, as of 20 milligauss or less, in which the field direction abruptly reversed itself. This region **34** of field reversal was moved out of the beam path **6** by shaping the portions **33** of the pole faces of the multipole magnet **26** which are nearest the opposite pole of the C-field magnet.

Referring now to FIG. 4, the prior art region of field reversal **34** is shown in dotted lines and was produced in the beam path **6** near the entrance and exit of the tubular extensions **24** of the C-field magnet **21** by the leakage of flux between the end regions of the tubular magnet extensions and the poles of the multipole magnet **26** which are of opposite polarity. It is seen that such leakage flux is counter to the direction of flux inside the C-field magnet and, therefore, produces a region of weak field in which a field reversal takes place.

The pole face portions **33** of the multipole magnet, which are of opposite sign to the nearest end portions of the tubular extensions of the C-field magnet, are shaped such that they are moved away both in the axial and radial direction. This reduces the leakage flux to or from the C-field magnet **24** in the region adjacent the opposite pole of the multipole magnet thereby moving the region of field reversal **34** transversely out of the beam path as shown by the solid lines. Moving the region **34** of field reversal out of the beam **6** thereby inhibits the undesired Majorana transitions. The precise shape of the pole face **33** is not critical. However, the region of field reversal **34** will move with changes in the position of the pole face **33** generally in the same direction as the change in position of the pole face **33**. Rounding off the corner of the pole face of the magnet **27** is found to be very satisfactory. Of course, the multipole magnet assemblies **8** and **13** are similarly shaped, as indicated in FIG. 1, to avoid Majorana transitions.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. An atomic beam tube apparatus including means forming a source of beam particles for forming and projecting a beam along an elongated beam path, means forming a first multipole energy state selecting magnet disposed along the beam path for deflecting out of the beam path certain atoms of non-selected energy states and retaining in the beam path other atoms of certain selected energy states, means forming a C-field magnet structure having a north pole and a south pole axially spaced along the beam path for producing a region of relatively weak and uniform magnetic field within the beam path and directed along a direction parallel to the beam path, means for applying an alternating magnetic field to the beam in said C-field region of relatively weak uniform field produced by said C-field magnet structure, the frequency of the applied alternating magnetic field being at the field independent hyperfine resonance frequency of the selected atoms within the beam to produce hyperfine resonance of the atoms in the beam, means forming a second multipole energy state selecting magnet disposed along the beam path downstream from the C-field region, means for detecting atoms of the beam deflected by said second state selecting magnet means to indicate hyperfine resonance, each of said first and second multipole state selecting magnet means including at least four magnetic pole pieces disposed around the beam facing the beam path and alternating in polarity between north and south taken in a direction around the beam path, portions of said multipole magnet pole pieces which face the beam path and which are of the same polartiy as the adjacent

C-field magnet structure being formed with a rectangular cross-sectional shape, and portions of said multipole magnet pole pieces which face the beam path and which are of opposite polarity to the adjacent C-field magnet structure being tapered in cross section toward the axis of the beam in a direction along the beam axis and away from the C-field to provide greater distance from said last named pole portions to the beam axis than the corresponding pole portions of said other pole pieces of opposite polarity, whereby regions of very weak C-field near an end portion of said C-field magnet are moved transversely off the axis of the beam path to inhibit Majorana transitions of the atoms of the beam.

2. The apparatus of claim **1**, wherein said C-field magnet structure comprises an electric solenoid, and a magnetically permeable shell enveloping said solenoid and serving as the magnetic return yoke for said solenoid.

3. The apparatus of claim **2** wherein said shell is apertured in alignment with the beam path for passage of the beam therethrough, and including a tubular neck portion projecting axially toward said state selecting magnet structure with the beam path passing axially through said neck portion.

4. The apparatus of claim **3** including, a magnetically permeable shell enclosing said state selecting magnet and forming a magnetic shield for said state selecting magnet structure, said state selecting shield having a pair of apertures in alignment with the beam path for passage of the beam through said state selecting magnet and said shield therefor.

5. The appartus of claim **4** including, a magnetically permeable shell enveloping said C-field magnet yoke and said tubular extensions thereof for shielding the C-field region of said C-field magnet from external magnetic fields.

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WILLIAM F. LINDQUIST, *Primary Examiner.*