THE ATOMIC HYDROGEN MASER*

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ABSTRACT

The basic principles of the atomic hydrogen maser will be described. Since a hydrogen maser emits a highly stable radio frequency signal, it can be used not only for accurate atomic measurements but also in other fields, such as navigation and radio astronomy where a highly stable clock is required. Results of hydrogen maser measurements are given.

INTRODUCTION

The atomic hydrogen maser depends on hyperfine transitions of atomic hydrogen in its electronic ground state.

The energy levels of atomic hydrogen in its electronic ground state are shown in Fig. 1. In weak magnetic fields the higher energy $F = 1$ states correspond to the electron and proton spins being parallel while the spins are antiparallel in the $F = 0$ state. With the hydrogen maser the transitions between the various hyperfine energy levels of Fig. 1 have been studied under various conditions.

The Hydrogen Maser

The atomic hydrogen maser was first developed at Harvard University by Kleppner, Goldenberg, and Ramsey [1-4]. A schematic diagram of the hydrogen maser is shown in Fig. 2. Since ordinary hydrogen that comes in a storage tank is molecular hydrogen (H_2) rather than atomic hydrogen (H), it is first necessary to convert the molecular hydrogen to the atomic form. This is done by admitting the molecular hydrogen into a small quartz or Pyrex bulb which forms the atomic hydrogen source. This bulb is surrounded by a coil of wire which is excited with a standard radio-frequency oscillator such as is used in a small radio broadcasing station. The oscillating field from this coil establishes a gas discharge in the bulb similar to the familiar gas discharge in a neon advertising sign. In this gas discharge the molecules of hydrogen are broken up into atoms, and most of what emerges from a small hole in the source bulb is atomic hydrogen.

The atoms of hydrogen emerge into a vacuum region which is exhausted to a low pressure (less than 10^{-6} Torr). In such a low-pressure region

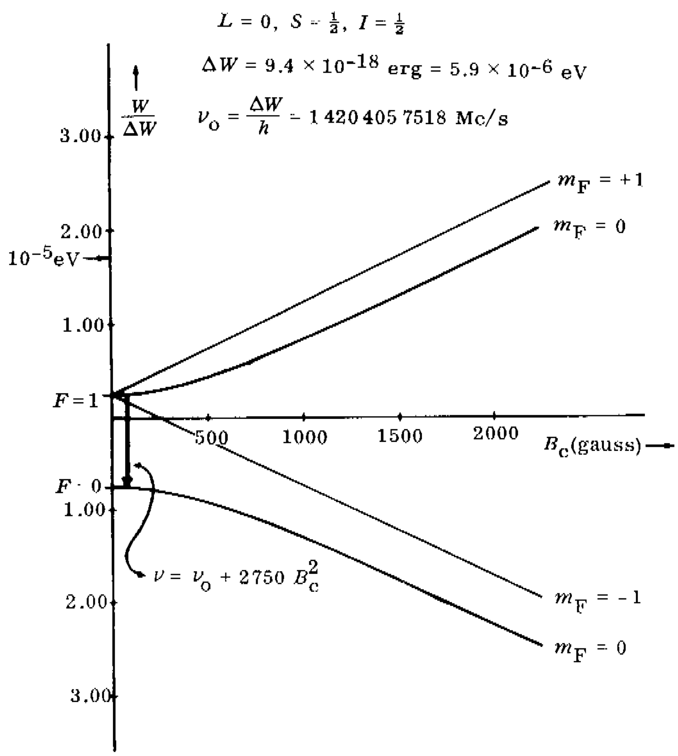

Fig. 1. Atomic hydrogen hyperfine structure showing the dependence of the energy levels on the strength of an external magnetic field. The heavy arrow indicates the transition ordinarily used in stable atomic hydrogen oscillators.

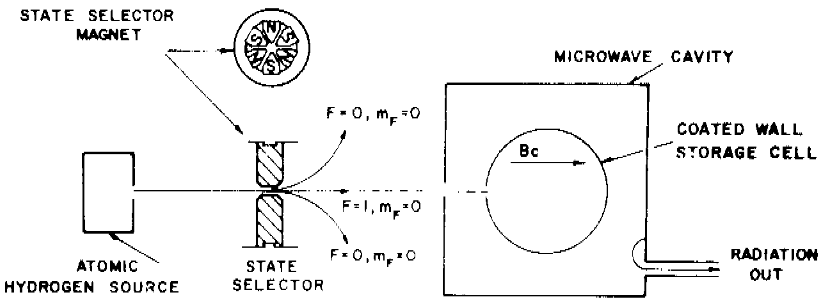

Fig. 2. Schematic drawing of atomic hydrogen maser

the atoms will travel in straight lines unless acted upon by a force. In particular, some of the atoms will go straight through the state selector magnet, as shown in Fig. 2. The state selector magnet has six poles, half on which are north poles and half south poles, arranged as shown schematically in the cross section in the upper portion of Fig. 2. By symmetry, the magnetic field must be zero on the exact central axis of the magnet. On the other hand, if the atom goes slightly off the central axis, the magnetic field will rapidly increase. Consequently, then energy of the atom will change when it is off axis. If the atom is in the $F = 0$ state, its magnetic energy will decrease as the atom gets farther off the axis as can be seen from Fig. 1. Since atoms prefer to go in the direction where the energy is lower, an atom of hydrogen in the $F = 0$ state which is off the central axis will be subject to a force pulling it still farther off the central axis. Therefore, such atoms will be defocused by the state selector magnet. On the other hand, the energies of the $M_F = +1$ and 0 states for atoms with $F = 1$ increase as the atom gets farther off the axis. Consequently, the force on it pushes it back toward the axis; i.e., it is focused. The dimensions of the magnet are selected in such a fashion that the $F = 1$ atoms are focused on a small hole in a 6-in.-diam Teflon-coated quartz storage bulb.

As a result of the above focusing action on the F = 1 state and the defocusing action on the F = 0 state, the quartz bulb is dominantly filled with atoms in the higher-energy F = 1 state. The bulb is also surrounded by a microwave cavity tuned to the 1420-MHz frequency, characteristic of atomic hydrogen. Since the atoms in the bulb are dominantly in the higher-energy state, this arrangement satisfies all the requirements for maser amplifications. Indeed, such a device can be used as an amplifier. Moreover, if the amplification is sufficient it can also be a self-running oscillator. It is easy to see how oscillation can be established in such a device. If there is a weak noise signal present at the appropriate 1420-MHz frequency, stimulated emission will exceed absorption and the original signal will be amplified to a larger one which will be further amplified. The signal will thus get bigger and bigger up to the point where most of the energy being brought into the bulb by the atoms in the higher-energy state is absorbed. At this condition an equilibrium steady-state oscillation will be established. Although the power in the oscillation is quite weak -- about 10^{-12} W -- the oscillation is highly stable and is concentrated in an unprecedentedly narrow frequency band. Consequently the signal can easily be seen despite its low total power. Ordinarily the atoms are stored in the bulb for about one-third of a second, during which time each atom makes over 10,000 collisions with the wall of the containing vessel.

An electrical coupling loop is inserted into the cavity so that some of the microwaves' oscillatory power can be coupled out for observation. The signal that emerges from such a maser proves to be unprecedentedly stable. This highly stable signal provides the basis for the experiments which will be described in the latter portion of the present report.

A photograph of a hydrogen maser is shown in Fig. 3. The entire device is about 4 ft. tall. The vertical cylinders are vacuum pumps, and the large cylinder with a horizontal axis is the tuned microwave cavity. Inside that cylinder is the Teflon-coated quartz bulb containing atomic hydrogen dominantly in the high-energy F = 1 hyperfine state. In normal use the microwave cavity is further surrounded by three successive concentric layers of molypermalloy, which shields the apparatus from the magnetic disturbances in the room.

A photograph of the six-pole focusing magnet used in the hydrogen maser is shown in Fig. 4. The six Alnico magnets are shown in the photograph. The poles of the magnets alternate successively north and south. The atomic beam goes along the axis of the cylinder.

The unprecedentedly high stability of the maser microwave oscillation arises from a combination of four desirable features, all of which contribute to increased stability. These factors include:

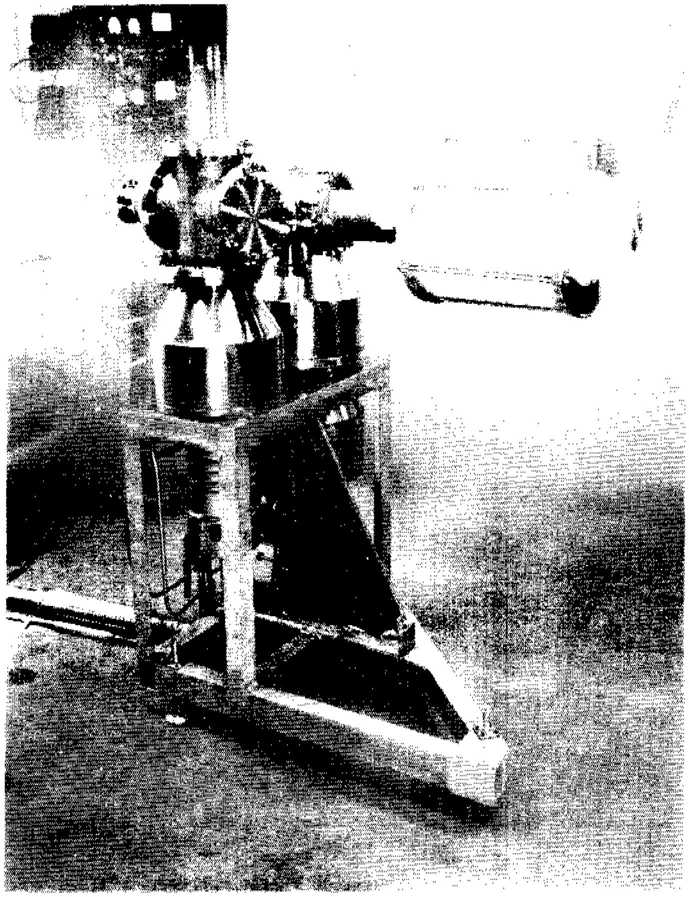

Fig. 3. Photograph of hydrogen maser

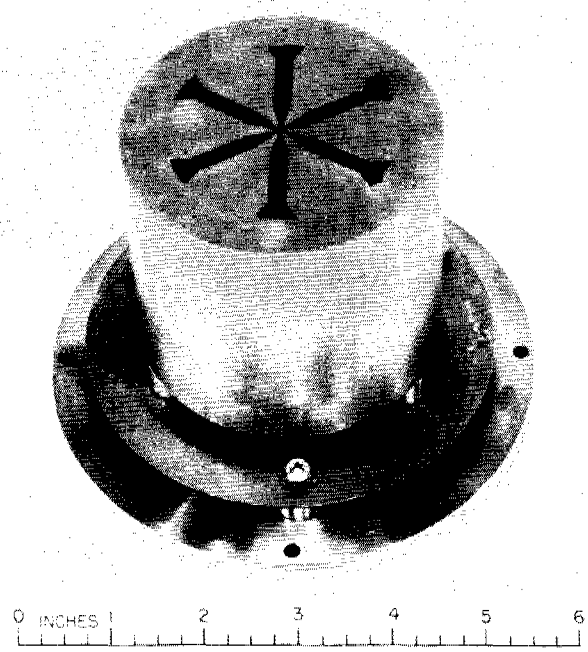

Fig. 4. Photograph of six pole focusing magnet

(a) The atoms reside in the storage bottle for a much longer period of time than the atoms remain in a normal molecular beam apparatus. Consequently the characteristic resonance line is much narrower and the output signal is more stable, since the peak of a narrow line can be much more accurately located than the peak of a broad line. The narrowing of the line is just that to be expected from the Heisenberg Uncertainty Principle. According to this principle, a longer observation time makes possible a narrower resonance and consequently a more stable frequency. The narrowness of the resonance also diminishes the pulling of the maser frequency by any mistuning of the microwave cavity; in addition the cavity can be accurately tuned by adjusting its tuning to be such that the output frequency is independent of the intensity of the beam of hydrogen atoms [3,5]. It has been shown by Crampton [5] that this method of cavity tuning eliminates the effect of a spin exchange frequency shift except for a small measurable shift of a few parts in 10^{13} due to the change in hyperfine frequency during the time of the collision [5].

(b) The atom is relatively free and unperturbed while radiating, unlike an atom in a resonance experiment using liquids, solids, or gases at relatively high pressure. Consequently, all atoms will have the same characteristic frequency, and the resultant resonance will not be broadened as it would be if it consisted of a superposition of a number of resonance at slightly different frequencies. Unfortunately the atoms of hydrogen are not totally free, since they must collide at intervals with the Teflon-coated wall of the storage bulb. This produces a shift in the maser frequency of about 2 parts in 10^{11}. This correction, however, can be experimentally determined by observing the frequency of the output with bulbs of two different sizes and then by extrapolating to a bulb of infinite diameter as discussed later in greater detail.

(c) A further advantage of the hydrogen maser is that the first-order Doppler shift is greatly reduced. With the very-narrow-line characteristic of the atomic hydrogen maser, the relevant quantity for the Doppler shift is the ratio of the average velocity of the hydrogen atom to the velocity of light. Since the hydrogen atoms enter the storage bulb through a small hole, and then stay in the storage bulb for about 1 sec. before finally emerging from the same hole, the average velocity is zero, or close to zero. Consequently the first-order Doppler shift is completely negligible. There is a small second order Doppler shift due to the relativistic slowing down of any moving clock or oscillator. Since the second-order Doppler shift depends upon the velocity squared, it is not averaged to zero while the atom is in the bulb. On the other hand, the second-order Doppler shift is a correction that can be exactly calculated if the temperature and hence the mean square velocity of the atom is accurately known.

(d) A final advantage that contributes to the high precision of the atomic hydrogen maser is the low-noise characteristic of maser amplification. Since the amplifying element is an isolated simple atom, there is little opportunity for any extra noise to develop beyond the theoretical minimum noise. As a result, the maser is a very-low-noise amplifier, and the oscillation will be much more stable since the frequency is less likely to drift to a nearby noise peak.

For the above four reasons the hydrogen maser frequency should be very stable. This prediction has been confirmed experimentally and the stability, as measured by the Allan variance, is about 2×10^{-15}. For many experiments stability is all that is required for the desired measurements. On the other hand, often the observer wishes to know the absolute rate of the oscillation in terms of those of a totally free hydrogen atom. In such cases the correction for the wall shift must be known. This correction can be determined by making measurements with storage bulbs of two different sizes, the necessity for making the correction usually degrades the accuracy and a further degradation of the accuracy of absolute measurements come from the necessity of measuring the cesium hyperfine structure as the standard of time. The wall shift correction can, however, be made more reliably if a single storage bulb is used whose shape can be deformed to change the ratio of the surface area to the volume, as discussed further in section.

Large Storage Box Hydrogen Maser

In the previous discussion it has been mentioned that the principal source of uncertainty in the hydrogen maser measurements arises from the necessity of making a wall shift correction for the effect of the wall upon the hydrogen atom when the atom is in the vicinity of the wall. Although this correction can be made by extrapolating results on masers with a different sized storage bulbs, the uncertainty in the determination of the wall correction remains the principal source of uncertainty in many of the maser measurements. Zitzewitz [11,12] and Vessot [13] are undertaking experiments to reduce this uncertainty by finding a wall-coating material that is superior to Teflon. So far, however, Teflon remains the best wall-coating substance.

An alternative means of reducing the effect of the wall shift has been accomplished by Uzgiris [10] in our laboratory. He has constructed a maser with a storage box that is ten times larger in diameter than the normal 6-in.-diam. storage bulb. Since the atom will strike the wall only one-tenth as frequently in such a storage box, the wall shift will be ten times less. In addition, a longer total storage time can be arranged, which makes the resonances even sharper.

A schematic diagram of the large storage box hydrogen maser is shown in Fig. 5. The arrangement of this maser is necessarily different from that of previous hydrogen masers and a number of new principles involved. In particular the cavity can no longer surround the entire storage box, since the wavelength of the radiation is small compared to the diameter of the storage box. However, an equally narrow resonance is obtained if the cavity in which the maser oscillation occurs surrounds only a portion of the storage box, provided the atoms make a number of transits between the small storage box and the large box before finally exiting through the entrance cavity of the large box. Since the atoms are in the region of the cavity only for a very short period of time, it is necessary to have a higher level of excitation than would occur from simple spontaneous maser oscillation. As a result two cavities are used, each surrounding a small portion of the storage box and about 80 dB of amplifier gain is provided between the two cavities. In this manner the atoms are placed in a superradiant state by the intense oscillations in the high-level driving cavity and are thereby able to produce spontaneous maser oscillation in the low-level cavity, which in turn is amplified to the high-level driving cavity.

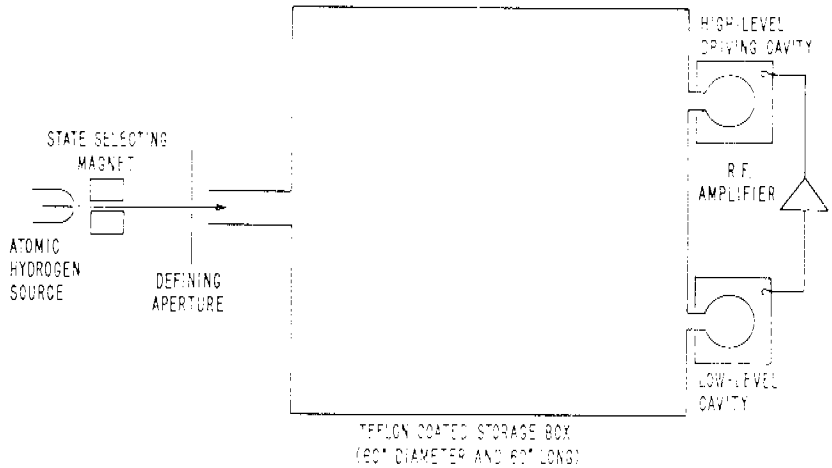

Fig. 5. Schematic diagram of large box hydrogen maser

Wall and Gas Collisions

Zitzewitz and Ramsey [11,12] have studied the Teflon wall shifts at different temperatures with the results shown in Fig. 6. One interesting result was the observation that at about 80°C the wall shift passes from positive to negative values and consequently vanishes at the crossing temperature. This feature is of value in maser experiments that are limited by the wall shift. Zitzewitz [11,12] also found that the abrupt changes with temperature in the slope of the wall shift curve in Fig. 6 are correlated to known phase changes in Teflon.

Until recently all frequency shifts due to wall collisions were measured by extrapolation with the use of Teflon-caoted storage bulbs of different diameters. However, Zitzewitz, Uzgiris, and Ramsey [11] showed that the accuracy of this extrapolation was reduced by the differences in the wall coatings on the different bulbs. Brenner [14] pointed out that this difficulty could be overcome by the use of a single flexible storage bulb whose volume could be altered while keeping the same surface. This technique was further developed by Debely [15] who used a storage cylinder, one of whose ends was a thin conical sheet of Teflon which could be in either of the two positions shown in Fig. 7. With

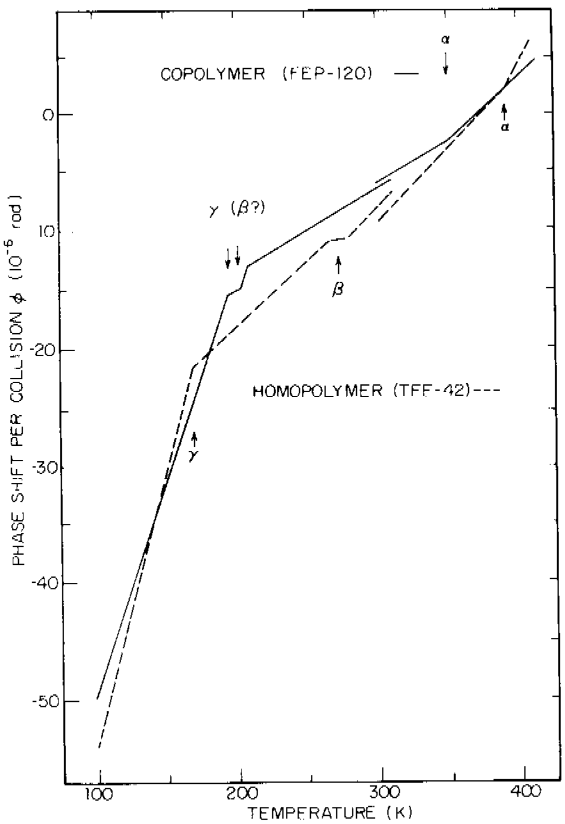

Fig. 6. Experimental phase shift per collision versus temperature

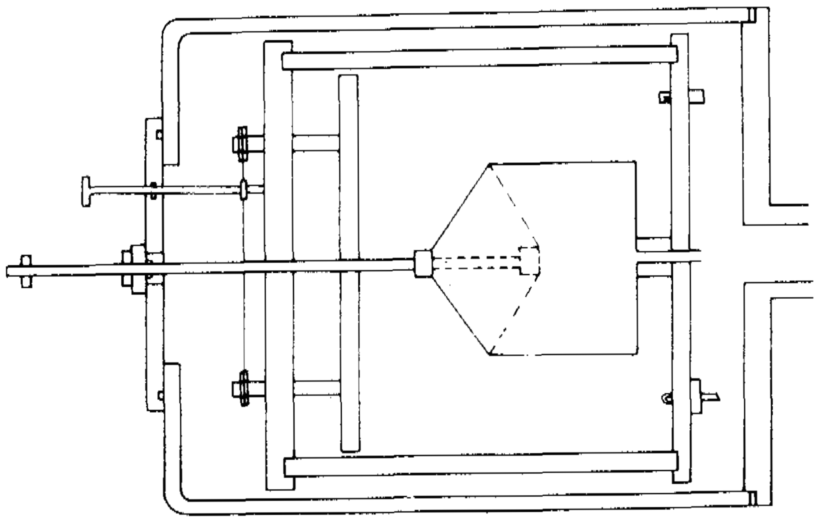

Fig. 7. Deformable bulb H maser [15]. The conical surface can be in the positions indicated by the full or dashed lines.

this deformable bulb technique the wall-shift measurements are all made on the same surface.

Reinhardt [16] has adapted this deformable bulb technique to the large box hydrogen maser by using the configuration shown in Fig. 8. An alternative to the use of the deformable bulb technique has been suggested by Vessot [13] who has proposed operating a hydrogen maser at the temperature where the wall shift vanishes [12] and using the deformable bulb to locate that temperature experimentally, i.e., to operate at the temeprature for which the output frequencies are the same in the two different deformable bulb configurations. Peters has used a variable volume maser in the form of a bellows.

Bender [18] first pointed out that spin exchange collisions of hydrogen atoms might produce a significant frequency shift in the hydrogen maser, but Crampton [19] noted that the normal tuning technique would cancel out such an effect. Later Crampton pointed out the existence of a smaller additional spin exchange effect that would not be cancelled by the normal tuning method. This effect was omitted in earlier

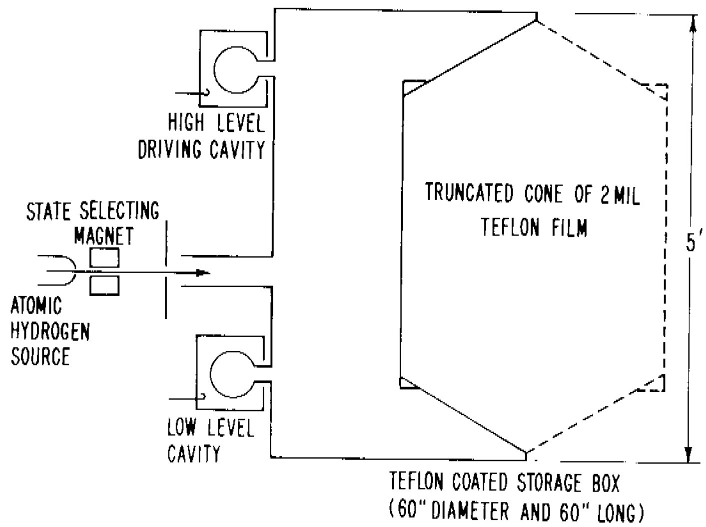

Fig. 8. Large storage box H maser with deformable bulb for measurement of wall shift [16].

theories due to their neglect of the contribution of the hyperfine interaction during the time of the short duration of the collision. Crampton developed a technique for measuring the spin exchange effect. Crampton also pointed out the existence of a small frequency shift due to magnetic field inhomogeneities; this small shift is often called the Crampton effect. Both of these effects are so small they did not effect past measurements and they can be further reduced by suitable apparatus design.

Applications

The hydrogen maser has been used both for precision measurements of the properties of the hydrogen atom and its isotopes and as a highly stable clock when other quantities are measured.

Some of the principal results of measurements of the properties of the hydrogen atom are given in Fig. 9.

ATOMIC ^{1}H, ^{2}D, and ^{3}T

$$\Delta\nu_H = 1,420,405,751.7680 \pm 0.0015 \text{ Hz}$$

$$\Delta\nu_D = 327,384,352.5222 \pm 0.0017 \text{ Hz}$$

$$\Delta\nu_T = 1,516,701,470.7919 \pm 0.0071 \text{ Hz}$$

$$\mu_p = 0.00152103221(2)$$

Bohr magnetons

$$\mu_J(H)/\mu_J(D) = 1.00000000722(10)$$

$$\mu_J(H)/\mu_J(T) = 1.0000000107(20)$$

Fig. 9. Some results of maser measurements of atomic hydrogen (H), deuterium (D) and tritium (T). $\Delta\nu$ is the hyperfine separation of the atom, μ_p is the magnetic moment of the proton and μ_J is the magnetic moment of the indicated atom.

The hydrogen maser has been used extensively as a high stability clock in long base line interferometry in radio-astronomy. It has also been used in various radio-astronomy tests of the theory of relativity. Vessot [21] has recently used a hydrogen maser in a high altitude rocket to test the equivalence principle in the theory of relativity.

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