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A COMPARISON OF ATOMIC FREQUENCY STANDARDS

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The historic work of Essen and Parry eight years ago on atomic frequency standards was followed by a vast amount of developmental research on these devices. A vast amount of data has been accumulated on cesium* beam standards which testifies to their practicality and provides a sound basis for confidence in them. The atomic devices have merit not only as frequency standards but also as standards of time; they provide a new basis for the redefinition of the second.

Newer atomic devices display at least some of the basic qualifications and have entered the competition with the cesium beam. Each one must be given fair trial so that the best system is chosen as the internationally accepted standard. As a practical matter, of course, it may be necessary to select the basic standard before all candidates can possibly be given the required painstaking evaluation.

Among these newer atomic standards are the thallium beam, the hydrogen maser, the rubidium gas cell, various gaseous microwave masers—the grandfather of which is the ammonia maser—and molecular beam electric resonance devices.

The National Bureau of Standards Boulder Laboratory is one of the several laboratories engaged in the development of atomic frequency standards and over the past several years has inter-compared and evaluated cesium beam devices [Mockler *et al.*, 1960; Mockler, 1961; Richardson *et al.*, 1961; Beehler *et al.*, 1962], ammonia masers [Mockler *et al.*, 1958; Barnes *et al.*, 1961; Barnes *et al.*, 1962] and is presently engaged in the evaluation of the thallium beam [Beehler and Glaze, 1963]. It is intended to evaluate the hydrogen maser. The laboratory has also accumulated a large amount of frequency data on commercial cesium beam and rubidium gas cell devices [Harper, 1962]. The inter-comparison and evaluation of three of these devices within the same laboratory is the subject of this paper.

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* Also spelled caesium.

Two laboratory cesium beam frequency standards were inter-compared over a period of three years. The longer of these two machines is shown in Fig. 1. The separation between the oscillating fields is 164 cm for this machine and 55 cm for the smaller machine. During this three year period practically all of the electronics was replaced and a number of the internal components of the beam apparatus were replaced including deflecting magnets, C field structures and the r.f. excitation structure of the smaller machine. Also, both machines were partially disassembled and moved to a different laboratory. With all of these changes the frequency difference between them remained within $\pm 2 \times 10^{-12}$ where the fixed relative frequency difference was 1.6×10^{-11}. The relative stability was typically $\pm 2 \times 10^{-12}$ for an averaging time of one-half hour. The best stability that we attained was $\pm 2 \times 10^{-13}$ (requiring an averaging time of ten hours). The statistical behavior was good; χ^2 tests demonstrated a gaussian distribution of the data. The accuracy is considered to be $\pm 1 \times 10^{-11}$. Confidence in this accuracy figure is given by the agreement between the frequencies of these two dissimilar machines. It is based on the results of a group of auxiliary experiments measuring the C field intensity and uniformity, the phase shift between oscillating field regions, the power spectrum of the exciting radiation, effects of neighboring resonances, cavity pulling, and the variation of frequency with power level. The composite uncertainty in the resonant frequency due to these various sources was determined for each of the machines; their sum exceeds the measured 1.6×10^{-11} fixed frequency difference. Nevertheless, this fixed frequency difference is still puzzling and implies the existence of a systematic error that has not yet been identified. Further study of this point is necessary.

The effect of neighboring transitions on the frequency of the $(F=4, m_F=0) \leftrightarrow (F=3, m_F=0)$ transition can be reduced to the point of insignificance by simply operating at sufficiently high values of the C field. This shift is, however, of considerable interest because there is not yet a suitable theory capable of predicting these observed shifts. Even so there are certain things that we can say about these shifts. The neighboring lines are symmetrically placed about the standard $(4,0) \leftrightarrow (3,0)$ transition both in frequency and intensity. As a consequence no frequency shift is expected in first order. The C field is oriented such that only the $\sigma(\Delta m_F = 0)$ transitions

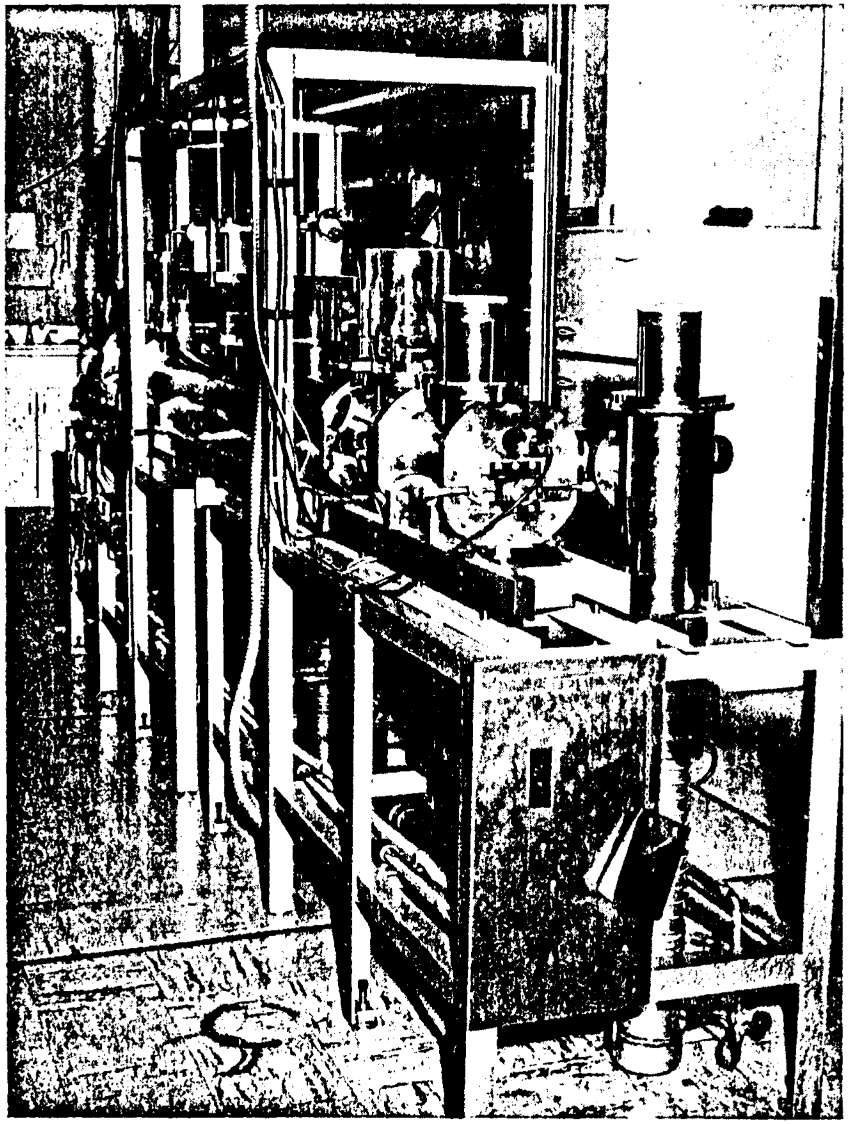

Fig. 1. Cesium atomic beam frequency standard (NBS II).

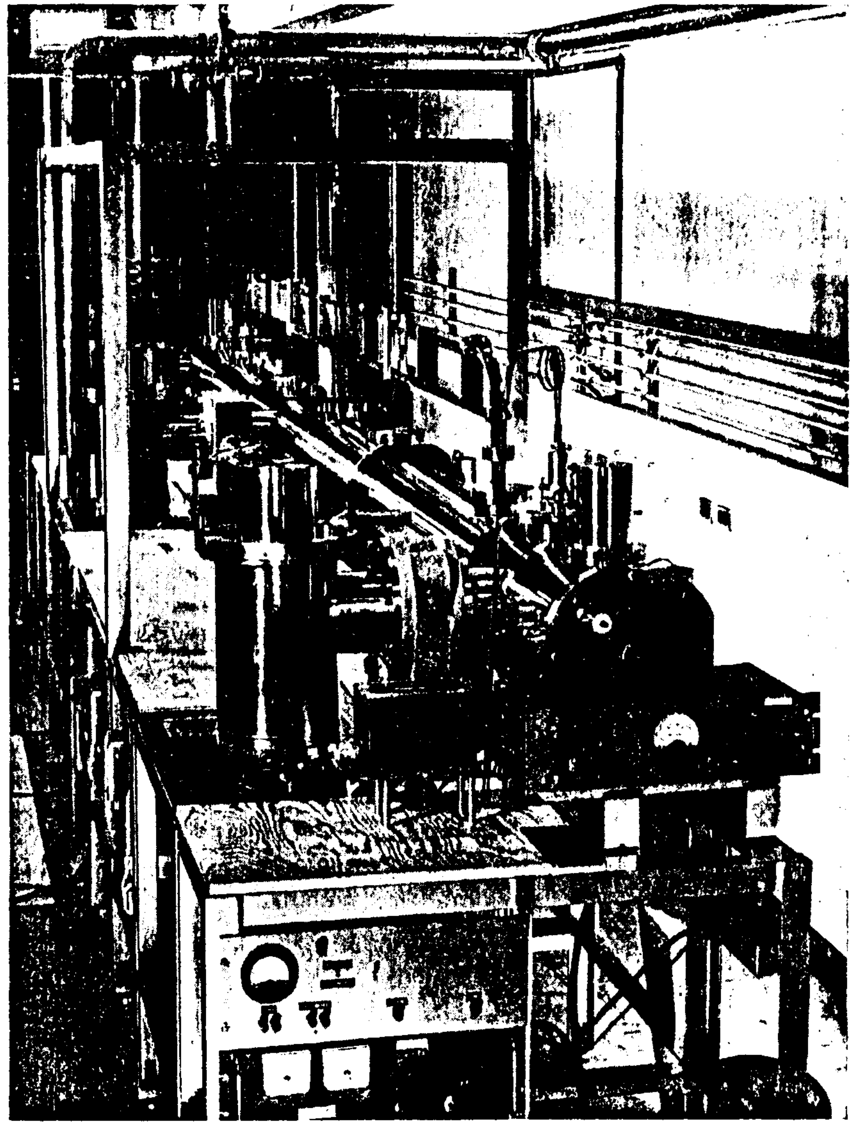

Fig. 2. Cesium atomic beam frequency standard (NBS III).

are observable. There is no observable trace of the $\pi(\Delta m_F = \pm 1)$ transitions. If the intensity of the π transitions were exactly zero then the matrix elements connecting adjacent m_F levels are all zero. This means that a shift can be determined by a simple superposition of all seven of the σ transitions. Under these circumstances there would be no shift if the spectrum were symmetrical. There are, however, geometrical factors in a specific instrument that will

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change the relative intensities of the various lines and one expects and can estimate a shift. When we set our C field at 20 millioersteds we observe a shift of 4×10^{-11} in frequency. We estimate from our relative intensity measurements the value 1.3×10^{-12} (assuming that the π transitions have exactly zero intensity). Further study is required on this matter.

The Bloch–Siegert type shifts have been calculated for this cesium transition and found to be entirely negligible [Shirley, 1963], as expected. The relative frequency shifts calculated are 3.8×10^{-15} for the short machine and 1.8×10^{-15} for the long machine.

Servo controls were placed on both machines. Manual and servo assisted measurements were compared and they agreed within $\pm 2 \times 10^{-12}$ after extensive development. For one year thereafter the agreement continued to be within the precision of the comparisons ($\pm 2 \times 10^{-12}$).

A newer and longer cesium beam machine is now under test. It is shown in Fig. 2. The separation between oscillating fields is about 3.7 meters and the Ramsey linewidth is about 48 c/s.

The accuracy for the cesium transition appears to be limited primarily by the sensitivity of the cesium transition to a magnetic field. Thallium is much less sensitive and in addition has a much simpler spectrum.

Our older and shortest machine was modified for observing the thallium $(1, 0) \leftrightarrow (0, 0)$ transition over one year ago. The modified instrument is shown in Fig. 3. Preliminary results in the evaluation of thallium as a frequency standard show a typical precision of 2×10^{-12} (one hour averaging time) and a best precision of about 5×10^{-13}. These are much the same as the corresponding values for cesium. In the initial experiments the waveguide excitation structure did not give reproducible results on rotation. After making the structure more rigid good reproducibility was attained. Presently the scatter in the day to day measurements (standard deviation $\approx 1 \times 10^{-11}$) is not sufficiently random as one would determine from a χ^2 test. This suggests some yet unidentified systematic errors. Our preliminary result for the zero field $(1, 0) \leftrightarrow (0, 0)$ transition frequency is: $\nu_0(\mathrm{T}l) = 21{,}310{,}833{,}946.5 \pm 0.4$ c/s. The assumption is made here that the cesium frequency is 9,192,631,770.00 c/s. The Neuchatel group obtained the value $\nu_0(\mathrm{T}l) = 21{,}310{,}833{,}945.1 \pm 1.0$ c/s in their earlier experiments [Bonanomi, 1962].

The accuracy of the preliminary results for thallium is still not as good as the accuracy of the cesium instrument. However, these initial results are encouraging, and we hope, perhaps optimistically, for an ultimate accuracy of 1 to 2×10^{-12}.

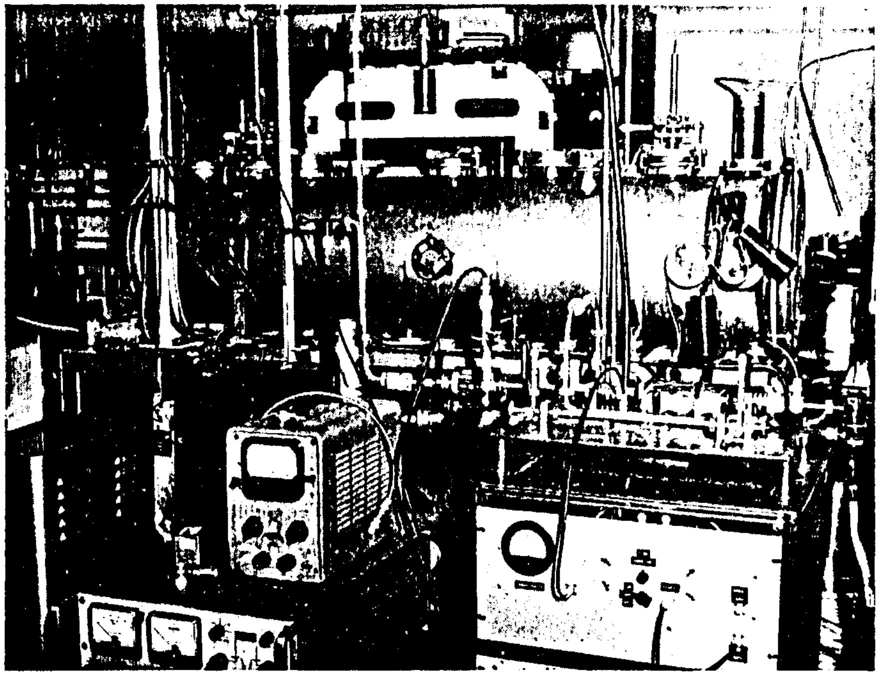

Fig. 3. The NBS thallium atomic beam frequency standard.

In past years two ammonia masers have undergone considerable testing at NBS. They were found to be resettable to within $\pm 3 \times 10^{-11}$ for $^{14}NH_3$. The stability was $\pm 2 \times 10^{-12}$ for periods of one hour. Experiments with $^{15}NH_3$ indicate that if two different systems were constructed they could be expected to agree in frequency within $\pm 4 \times 10^{-11}$ if a detailed prescription was adhered to. Similar results were obtained by De Prins [1962] and also by Saburi *et al.*, [1962] for the 3.2 line of $^{14}NH_3$. Because of the extreme care required to control the parameters affecting the maser frequency and because of the difficulties of relating the output frequency to the separation of the states for the isolated molecule, we do not consider the ammonia maser a competitor of the cesium beam.

We hope to have a hydrogen maser in operation shortly so that we may evaluate it as a primary standard of frequency. The hydrogen maser has a frequency shift resulting from collision processes—as does the optical gas cell device—that must be coped with before it can be expected to provide greater accuracy than cesium.

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