

RADIO PHYSICS

I. MOLECULAR BEAMS*

Prof. J. R. Zacharias
Prof. J. G. King
Prof. C. L. Searle
Prof. K. W. Billman

R. S. Badessa
V. J. Bates
J. F. Brenner
R. Golub
G. L. Guttrich

W. D. Johnston, Jr.
S. G. Kukolich
F. J. O'Brien
C. O. Thornburg, Jr.

A. CESIUM BEAM TUBE INVESTIGATION

Frequency comparison measurements have been made on two cesium clocks by using the new frequency-impulse modulation system described in Quarterly Progress Report No. 72 (pages 1-6). As was stated in that report, the NC-2001 beam tube construction does not permit cavity correction directly and, therefore, an electronic waveform correction technique was devised that would essentially perform the desired action. Subsequent testing showed that this waveform correction loop was adversely affecting the primary control loop. Extensive measurements performed on the NC-2001 tube showed that it is hard to cause a differential detuning of the individual cavities. As a result of these tests we decided to use only the primary control loop.

Data taken over two 12-hour periods (Fig. I-1) show the stability to be within ± 1 part in 10^{12} with a standard deviation of approximately 6×10^{-13} , both for 1-hour averaging times. Daily variations in the offset frequency were +0.5, -1, +0.2, +0.5, +0.1 $\times 10^{-12}$. On the day when the -1×10^{-12} variation occurred it is possible that the

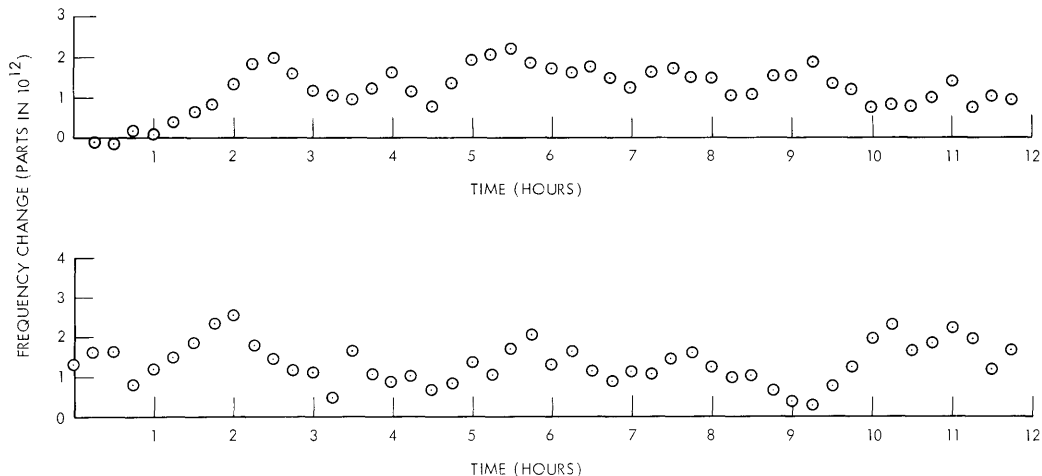


Fig. I-1. Frequency-stability data.

*This work was supported in part by Purchase Order DDL BB-107 with Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the U. S. Air Force under Contract AF 19(628)-500.

(I. MOLECULAR BEAMS)

vacuum in one of the tubes was deteriorating because of troubles occurring in the vacuum supply. No room-temperature stabilization was attempted for these measurements, although changes of 10-20°F were noted. These data were taken with the C-fields of the two beam tubes connected in series to minimize any frequency variations attributable to current supply drifts.

Several tests were also conducted on the electronic system with the results tabulated below.

| <u>Test</u> | <u>Results</u> |
|---|---|
| Servo gain $\pm 50\%$ from normal operation | Slight increase in short-term instabilities, long-term unaffected |
| RF power level ± 1 db | Effect in noise, less than 1×10^{-12} |
| Temperature cycling of silicon transistor used for synchronous detector | No effect over 25-75°C temperature range |

From the results of the tests reported here and of many others performed on electronic subsystems, and from the temperature cycling on the beam tube, any long-term drifts (1 hour or more) in frequency appear to be caused by changes in the magnetic field in the beam tube.

The magnetic-field dependence of the (4, 0-3, 0) transition is given by

$$f = f_0 + 427B^2, \quad (1)$$

where $f_0 = 9192.631770$ mc; B is in gauss; and f is the operating or clock frequency.

The B in Eq. 1 is the average magnetic field seen by a cesium atom while traversing the drift space between the two RF cavities. The sensitivity to changes in this field is given by

$$\Delta f = 5.1 \times 10^{-12} b, \quad (2)$$

where b is change in average field in milligauss, and Δf is change in operating frequency.

To measure the axial field sensitivity, cylindrical coils were wound around the wooden racks containing the beam tubes. It was found that the axial shielding is an order of magnitude poorer than the radial shielding. An axial field of 100 milligauss resulted in a frequency change of 4×10^{-12} which corresponds to an internal axial field change of approximately 1 milligauss. Stated shielding factors for radial fields are 1000, that

is, 1 gauss external produces approximately 1 milligauss.

An experiment now under way involves locating the precise clock frequency with respect to the zero-field frequency. Since the operating frequency offset is square-law dependent on the magnetic field (Eq. 1) the following tests are being conducted. After demagnetizing the C-field and microwave enclosure, the change in operating frequency is measured as a function of the current (both positive and negative) supplying the C-field coil. In Fig. I-2 is shown a typical curve obtained by this technique. Note that "majorama flop" prohibits taking measurements at low current levels. The solid curve

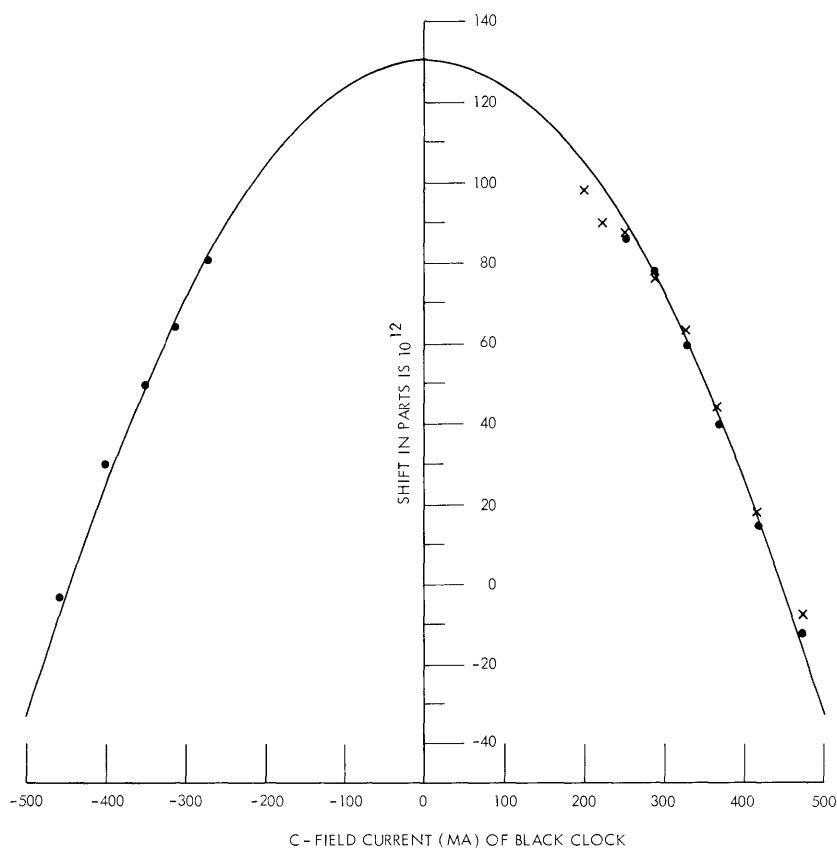


Fig. I-2. Square-law dependence of offset frequency.

represents the best-fit parabola. Since the curve should be completely symmetrical about the zero-current point, any offset is caused by a permanent field in the drift region of the beam tube. Similar tests will be performed on the orthogonal magnetic axis while operating at some known level on this curve.

R. S. Badessa, V. J. Bates, C. L. Searle

(I. MOLECULAR BEAMS)

B. AMMONIA MASER WITH SEPARATED OSCILLATING FIELDS

A two-cavity maser has been constructed with a cavity separation of 105 cm. This device employs Ramsey's method of separated oscillating fields to obtain a molecular resonance linewidth of 350 cps at 23 kmc. The 3-2 inversion resonance in ammonia was used with a servomechanism system to obtain a molecular resonance clock that, at present, has a stability of a few parts in 10^{10} . This system was also used as a high-resolution spectrometer to study the magnetic hyperfine structure of the 3-2 ammonia line.

The ammonia resonance clock system was used to compare the frequency of the 3-2 inversion resonance in ammonia with the hyperfine resonance in cesium. The ammonia signal was obtained by locking a harmonic of a crystal oscillator to the resonance with a servo loop. The cesium resonance signal was provided by V. J. Bates and R. S. Badessa from a National 2001 cesium beam tube. The A 1 time scale was used in these measurements. The A 1 system locates the cesium resonance at 9, 192, 631, 770 cps. The measurements were made over 100-sec intervals; 63 of these measurements were made on four separate days. The average of these measurements is 22, 834, 185, 108. 1 \pm 6. 2 cps. The standard deviation is 3 parts in 10^{10} , but the absolute accuracy may be much worse. The resonance frequency in the present device is quite dependent upon the power level of the stimulating signal. The frequency increases by one part in 10^9 for a 3-db decrease in stimulating power, and decreases by 2 parts in 10^9 for a 2-db increase in stimulating power. These changes were relative to the optimum stimulating power (transition probability is 1/2 in the first cavity). The frequency deviation of the present device appears to be a result of this power-dependent frequency shift. The dependence of the frequency on external magnetic fields or focuser voltage is much too small to be significant here.

The magnetic hyperfine structure of the 3-2 line in ammonia was investigated. The theoretical analysis of this line was reported by Hadley,¹ and subsequent measurements were made with 6-kc resolution by Shimoda.² We observed Ramsey resonance patterns

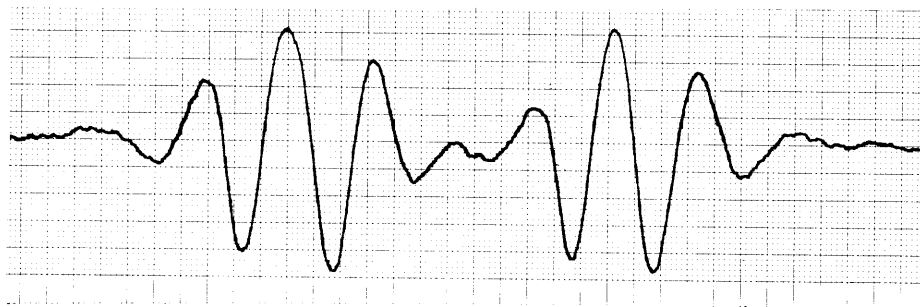


Fig. I-3. Resolved doublet (22, 834, 207. 2 kc and 22, 834, 210. 0 kc).

of 350-cps linewidth, and easily resolved the pairs of lines separated by less than 3 kc on each side of the main line. Our measurements agree with the form of the theoretical spectrum given by Hadley. The measured spectrum is symmetrical about the main line within the accuracy of our measurements. Figure I-3 shows the pair of lines at 22,834,207.2 kc and 22,834,210.0 kc as an indication of the resolution and signal-to-noise ratio of the system. The satellites have lower intensity than the main line by a factor of approximately 30.

The frequencies of the measured lines are:

- 22,834,247,950 \pm 100 cps
- 22,834,210,000 \pm 100 cps
- 22,834,207,200 \pm 100 cps
- 22,834,185,108 \pm 6 cps
- 22,834,163,000 \pm 100 cps
- 22,834,160,250 \pm 100 cps
- 22,834,122,250 \pm 100 cps.

A diagram of the apparatus is shown in Fig. I-4. The stimulating signal is applied to both cavities. A microwave receiver is connected to the second cavity in order to observe the resonance. A directional coupler is used at the second cavity to reduce the amount of stimulating power going directly into the receiver.

In the separated oscillating field scheme the resonance is shifted by a phase difference between the two fields. This shift has approximately the same dependence on the cavity tuning as with the single-cavity maser.⁴ But in this two-cavity maser the linewidth is much narrower so this device is more than an order of magnitude less sensitive to cavity tuning than the conventional ammonia maser.⁵ The phase difference between the RF fields is detected by modulating the phase of the stimulating signal with

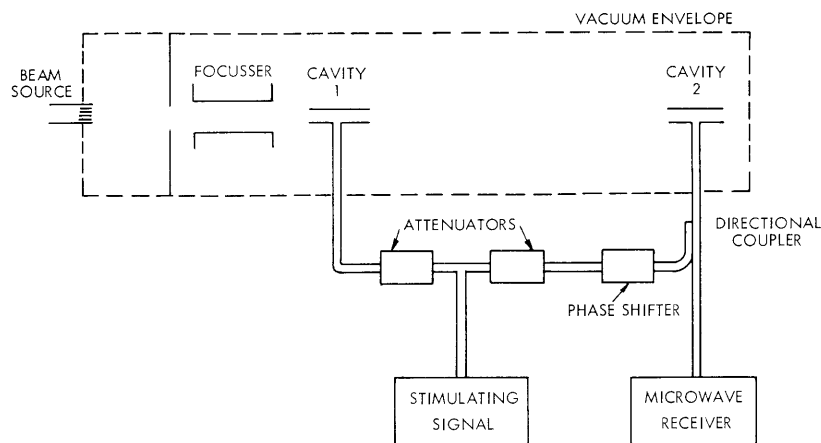


Fig. I-4. Diagram of the apparatus.

(I. MOLECULAR BEAMS)

a square wave and using a synchronous detector 90° out of phase with the modulation.⁶ This quadrature synchronous detector provides an output proportional to the phase difference between the RF fields. This signal is used to correct the phase difference. Another synchronous detector operating in phase with the modulation is used in a servo loop to control the frequency of the stimulating signal.

The two-level ammonia system is described by a wave function $\psi = \begin{pmatrix} a \\ b \end{pmatrix}$, where a is the complex amplitude of the upper inversion state, and b is the complex amplitude of the lower state. For our system the beam entering the first cavity is described by $\psi_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$, a beam containing only upper-state molecules. The Hamiltonian of this system is $\mathcal{H}_0 = \frac{\hbar\omega_0}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ if we adjust the energy scale so that zero is centered between the two inversion levels. The energy of the initial system is $\psi_0^* \mathcal{H}_0 \psi_0 = \frac{\hbar\omega_0}{2}$. The RF fields provide a perturbation of the form

$$\begin{pmatrix} 0 & \hbar b e^{-i\omega t} \\ \hbar b e^{-i\omega t} & 0 \end{pmatrix}$$

which causes transitions between the states $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$. This problem is solved for both the one- and two-cavity cases by Ramsey.⁷

The level and frequency of the RF field in the first cavity are such that the beam has the wave function $\psi_1 = \begin{pmatrix} e^{i\omega_0 t} \\ e^{-i\omega_0 t} \end{pmatrix}$ for the region between the cavities. If the first cavity is short compared with the cavity separation, the frequency range over which this condition is satisfied is large compared with the Ramsey resonance width. In the region between the cavities the perturbing fields are small, so the Hamiltonian is \mathcal{H}_0 and evaluating $\psi_1^* \mathcal{H}_0 \psi_1$ gives zero.

The energy of the beam molecules leaving the second cavity (E_f) is determined by Ramsey's equation for the total transition probability for the two-cavity system.

$$E_f = \hbar\omega_0 \left(\frac{1}{2} - P_{pq} \right) \quad P_{pq} \approx \sin^2 2b\tau \cos^2 \frac{1}{2} [(\omega_0 - \omega)T - \delta],$$

where τ is the transit time for each cavity, T is the transit time between cavities, and δ is the phase difference between the RF fields. Therefore the power delivered to the second cavity (P_2) must be $-nE_f$, where n is the number of molecules per second passing through the second cavity. Consequently, we see that measuring the power delivered to the second cavity provides a direct measure of the transition probability P_{pq} .

$$P_2 = -nE_f = n\hbar\omega_0 \left(P_{pq} - \frac{1}{2} \right).$$

Thus we obtain the typical Ramsey resonance curve by this method.

The important factor in the transition probability (P_{pq}) for $(\omega_0 - \omega) < 1/T$ is $\cos^2 \frac{1}{2}[(\omega_0 - \omega)T - \delta] = \cos^2 \frac{1}{2}\Phi$. A more general expression for Φ is $\Phi = \delta + \int_{t-T}^t (\omega_0 - \omega(\tau)) d\tau$. This reduces to the previous form when $\omega(\tau)$ is nearly constant over intervals of length T , that is, when the stimulating frequency is modulated very slowly.

Square-wave phase modulation of the stimulating signal produces a periodic step in Φ . The function Φ returns to zero (if $\omega = \omega_0$) in a time T after the step produced by the modulation. If the average value of $\omega = \omega_0$, the square-wave phase modulation will produce equal changes in $\cos^2 \frac{1}{2}\Phi$ for positive and negative steps. If the average value of ω is not at ω_0 , positive and negative steps in Φ will not produce equal changes in $\cos^2 \frac{1}{2}\Phi$ and the "in-phase" synchronous detector will indicate an error signal and correct the average value of ω .

If there is a phase difference δ between the RF fields, then the "in-phase" synchronous detector will adjust the average value of ω so that the average value of Φ is zero. The presence of this condition will be detected by the quadrature synchronous detector. If the period of the modulation is $4T_a$ (T_a is the average transit time between the cavities) the quadrature synchronous detector compares values of $\cos^2 \frac{1}{2}\Phi$ for $T < T_a$ with those for $T > T_a$. This provides the error signal that allows us to correct the cavity phase difference δ . This method has been discussed in greater detail by Bates and Badessa.⁶

S. G. Kukolich

References

1. G. F. Hadley, Phys. Rev. 108, 291 (1957).
2. K. Shimoda and K. Kondo, J. Phys. Soc. Japan 15, 1125 (1960).
3. G. F. Hadley, op. cit., see spectrum, p. 291.
4. S. G. Kukolich, Proc. IEEE 52, 211, 437 (1964).
5. K. Shimoda, T. C. Wang and C. H. Townes, Phys. Rev. 102, 1308 (1956).
6. V. Bates and S. Badessa, Quarterly Progress Report No. 72, Research Laboratory of Electronics, M.I.T., January 15, 1964, p. 1.
7. N. F. Ramsey, Molecular Beams (Oxford University Press, London, 1956), Chapter 5.

C. AMMONIA DECELERATION EXPERIMENT

A modified apparatus has been designed and work on its construction started. This apparatus differs from the previous one¹ in the following respects.

Deflection of the molecular beam by a nonuniform electric field will be used to provide velocity sensitivity. The beam will be detected by a detector based on the principle

(I. MOLECULAR BEAMS)

of high-field ionization. We have made experimental tests of the detector, using the device to measure the pressure in a vacuum system and calibrating it against an ionization gauge for various gases. No attempts to detect an actual beam have yet been made.²

Experimental results on high-voltage discharges in vacuum indicate that a 1-mm gap between invar electrodes can withstand voltages in excess of 30 kv. This allows the new apparatus to be considerably shorter than the old one. The decelerator will consist of 9 stages and will be approximately 8 inches long. Molecules will be decelerated from approximately 35°K to 1°K, or approximately a factor of 6 in velocity. (The source temperature will be approximately 100°K, so the output molecules will have $v = a/10$.)

Some theoretical work has been done on the focussing and phase-stability properties of the proposed decelerator. These problems have been treated to first order in deviations from the design trajectory. The focussing and phase-stability problems were assumed to be independent.

As the focussing properties depend on the geometry of the electrodes, these calculations were used to select the geometry.

The phase-stability characteristics depend primarily on the shape of the voltage pulse applied to the electrodes. The tops of the voltage pulses were assumed to have a linear drop in time. This will cause slow molecules that tend to arrive late at a given stage to lose less energy than fast molecules. Liouville's theorem (the fact that the volume in phase space occupied by a distribution of noninteracting molecules remains constant in time if the forces acting are conservative) indicates that the linear drop that produces bunching will not increase the intensity.

Let the direction of beam travel be the X direction. Then Liouville's theorem requires that (for a one-dimensional problem)

$$\delta x \delta p_x = \delta x \delta v_x m = \text{constant.}$$

But in order to calculate intensity, we are interested in distributions in arrival time rather than distributions in position,

$$\delta x = v \delta t$$

and the Liouville condition becomes

$$\delta t_{\text{out}} \delta v_{\text{out}} \left(\frac{v_{\text{out}}}{v_{\text{in}}} \right) = \delta t_{\text{in}} \delta v_{\text{in}},$$

where subscripts in and out refer to the input and output of the decelerator. δt_{out} is only limited to the half-cycle during which the voltage is on. δv_{out} will be determined by experimental conditions, that is, by the resolution of the velocity selector. The

(I. MOLECULAR BEAMS)

intensity is proportional to the product $\delta t_{in} \delta v_{in}$, ($\delta v_{in} \ll v_{in}$), so that for a fixed spread in output variables the intensity is fixed independently of voltage-waveform drop. For flat-top square waves only a small range of input velocities will produce output velocities in a given range, but the arrival time at the first stage will not have any appreciable effect as long as the molecules arrive during the half-cycle when the voltage is on. If, on the other hand, there is a fairly large linear drop (20 per cent) at the top of the pulses, a wide range of input velocities will be bunched into a given output velocity range, but this will occur only for those molecules that arrive at the first stage during a relatively small time interval.

Although the intensity is independent of waveform at the tops of the pulses, some drop is desirable, in order to provide stability against random errors in construction and voltage and frequency instability.

R. Golub, G. L. Guttrich

References

1. J. R. Zacharias and J. G. King, Linear Decelerator for Molecules, Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., January 15, 1958, pp. 56-57.
2. See also T. L. Hawk and J. F. Prather, Application of Field Ionization to Molecular Beam Detection, S.B. Thesis, Department of Physics, M.I.T., June 1964.

D. LOW-TEMPERATURE HELIUM BEAM EXPERIMENT

The initial design phase of this experiment has been completed during the past quarter and construction of an apparatus is now under way. The design capabilities of the apparatus are such as to permit the following studies.

1. Production and detection of atomic beams of helium, utilizing either gas or liquid sources at operating temperatures from $\frac{1}{2}^{\circ}\text{K}$ to 4.2°K .
2. Semiquantitative velocity analysis of the beams.
3. Data on intensity fluctuations ("shot noise") and correlation interference effects for gas and liquid sources.

To permit these studies, a detector for helium with a fairly fast resolving time and high efficiency is required. For correlation or interference studies a "small" detector, in terms of angular aperture seen from the source, is also necessary. After tests on an "Omegatron" mass spectrometer with an electron bombardment ion source had indicated a detection efficiency several orders of magnitude too small, because of low ionization probability, a field-ionizing detector was chosen.

This form of detector is essentially the same as the field-ionization microscope in operation, with a sharp ($\sim 1000 \text{ \AA}$ tip radius) tungsten needle operated at +50-90 kv exposed

(I. MOLECULAR BEAMS)

to the beam. Field-ionized atoms are repelled from the tip to a phosphor screen viewed by a photomultiplier. The practical resolving time is limited by the phosphor's rise and decay times (5×10^{-8} sec $1/e$ decay time for P-16 phosphor), and the efficiency is ~ 25 -30 per cent, determined by the solid angle of the phosphor screen seen by the needle tip. For 1°K helium atoms, the detector "size" is approximately 50 times the tip's physical radius or approximately 10^{-6} cm^2 cross-section area. For beam intensities of 10^6 atoms/sec the detector chamber residual pressure must be below 3×10^{-10} torr for acceptable signal-to-noise ratio, since the detector functions as a total pressure manometer. It is possible, however, that atoms other than helium, since they are more easily ionized, will have less energy upon hitting the phosphor and can be taken out of the signal by pulse-height discrimination following the photomultiplier stage.

Since the source end of the apparatus must fit into a dewar, all pumping lines, etc. must come out the detector end. This complicates the pumping problem of removing background gas from the beam chamber. It was decided to introduce an adsorption pumped separating chamber between the source and the velocity analyzer. This consists of a thin-wall copper tube, 12 in. long, 1-1/4 in. O. D., filled with Zeolite except for an axial hole of ~ 3 -mm diameter for the beam to pass through. Such a "trap" was tested at 4°K and showed a sticking probability for He of 99.999 per cent ($1 - 10^{-5}$) or greater, and did not saturate after adsorbing half a mole of helium.

Velocity analysis is to be accomplished with a single disc chopper that admits a pulse of 2-msec duration, repeated 10 times a second, through a 30-cm drift space to the detector.

The source end of the separating chamber is designed to accept either a gas source or a liquid source, with provision for use of an He^3 refrigeration cycle to further cool the liquid source. A reliable method for filling the liquid source remains to be devised.

W. D. Johnston, Jr.