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NEW MEASUREMENTS OF THE COSMIC MICROWAVE BACKGROUND AT $\lambda = 3.2$ cm AND $\lambda = 1.58$ cm—EVIDENCE IN SUPPORT OF A BLACKBODY SPECTRUM[*]

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In an effort to delineate the spectrum of the cosmic blackbody radiation, we have made more accurate measurements of the intensity at wavelengths of 3.2 and 1.58 cm. The results, combined with that at $\lambda = 8.56$ mm reported in the preceding Letter, indicate that over this wavelength range the spectrum is that of a black body at $2.68^{+0.09}_{-0.14}$ °K. In particular, a hot greybody spectrum does not fit the results.

Dicke et al.[1] have suggested that the recently discovered cosmic microwave background radiation[2] is the remnant radiation from the big-bang fireball.[3] The decisive tests of this idea are to measure the spectrum and the isotropy of the radiation: The spectrum should be that of a black body and the radiation should be nearly isotropic. Measurements made at Princeton last year indicate a high degree of isotropy[4]; we report here, and in the preceding Letter,[5] precision measurements of the microwave background intensity at $\lambda = 3.2$ cm, $\lambda = 1.58$ cm, and $\lambda = 8.56$ mm. The results indicate that the radiation is that of a 2.7°K black body.

To be convinced that one is seeing true blackbody radiation, and not that of a hot grey body, it is necessary to go to short wavelengths and look for the curvature in the spectrum due to quantum effects. The approach which we have taken is to modify conventional microwave radiometer techniques to make absolute measurements and to observe from the ground. The main limitation in pursuing short wavelengths is atmospheric radiation, which generally increases rapidly for wavelengths less than $\lambda = 2$ cm. To reduce the atmospheric background, the observations reported here and in Ref. 5 were made from an altitude of 12 470 ft at the Barcroft facility of the White Mountain Research Station, Bishop, California.

The technique used in these measurements is described in the preceding Letter. The optimum horn antennas were designed to give about the same beam width (10 dB down at ~4°) as that of the 8.56-mm radiometer, so that the same reflector could be used in all three measurements. All three instruments also used the same cold load as a reference source. Since the longer-wavelength antennas necessarily have larger apertures, it was necessary to break the horns at a point in the taper where the horn diameter matched the diameter of the cold-load pipe. Then the reference measurement was made by removing the large end of the horn and coupling the cold load to the small end. Measurements of the sky were made by replacing the cold load with the flare which completed the optimum horn. Otherwise, the radiometers are similar to the one sketched in Fig. 1 of Ref. 5.

The results of the 3.2-cm measurements are shown in Table I. Column 3 shows the observed change in radiometer output when the cold load replaces the sky as the radiation source. Column 4 lists the values obtained for the atmospheric radiation. Typically, the atmospheric temperature is 3°K at sea level for 3.2-cm wavelength. The fifth column shows the contribution to cold-load radiation due to reflections from the imperfect absorber. The cold-load absorber was improved after each of the first two runs.

From other measurements[5] at 3.2-cm wavelength it was determined that the cold-load wall emitted at a radiation temperature $T_{\mathrm{WALL}} = 0.16 \pm 0.10$°K, the aluminum reflector emitted at $T_{\mathrm{REFL}} = 0.08 \pm 0.06$°K, and the Styrofoam window at the top of the cold-load pipe emitted at $T_{\mathrm{WINDOW}} = 0.06 \pm 0.02$°K. Combining these with the temperature of boiling helium, $T_{\mathrm{He}} = 3.77$°K, we get

$$T_{\mathrm{He}} + T_{\mathrm{WALL}} + T_{\mathrm{WINDOW}} - T_{\mathrm{REFL}} = 3.91 \pm 0.13^\circ\mathrm{K}. \qquad (1)$$

Included in the error in Eq. (1) is a possible error of ±0.02°K due to uncertainties in the beam angles actually used to measure T_{ATM}, and an error of ±0.04°K to account for possible deviations of the atmospheric-temperature measurements from the calculated dependence on zenith angle. Equation (1) is added to the results of each run in Table I, according to

Table I. Results of all runs made with the 3.2-mm radiometer.

Date	Approx.^{a}	$T_{SKY} - T_{CL}$^{b} (°K)	T_{ATM}^{b} (°K)	T_{CLR}^{b} (°K)	T_{BG}^{c} (°K)	Wt.
7/10/67	16:30	4.85 ± 0.10	5.71 ± 0.25	0 ± 0.01	3.13	0.26
7/19/67	04:00	4.17 ± 0.09	5.75 ± 0.15	0 ± 0.01	2.41	0.38
7/22/67	05:30	4.06 ± 0.05	5.78 ± 0.25	0 ± 0.01	2.27	0.33
7/23/67	05:00	6.33 ± 0.09	7.36 ± 0.25	0 ± 0.01	2.96	0.26
7/26/67	13:00	5.54 ± 0.03	7.08 ± 0.25	0 ± 0.01	2.45	0.32
7/27/67	23:30	5.32 ± 0.02	6.28 ± 0.07	0 ± 0.01	3.03	1.00
8/11/67	03:00	4.38 ± 0.07	6.30 ± 0.10	0 ± 0.01	2.07	0.53
8/11/67	06:30	4.45 ± 0.06	6.18 ± 0.15	0 ± 0.01	2.14	0.43
8/19/67	03:00	6.19 ± 0.10	7.68 ± 0.25	0 ± 0.01	2.50	0.26
8/19/67	09:30	6.20 ± 0.20	7.48 ± 0.15	0 ± 0.01	2.71	0.26

[a] Declination = 37° 30'.

[b] Errors are standard deviations in the mean, or limits of drift, whichever is larger.

[c] Not yet corrected to thermodynamic temperature.

Eq. (3) in Ref. 5, to obtain the values for the background temperature in column 6. The weight assigned to each run is derived from the statistical errors in columns 3, 4, and 5. A weighted average of the results gives $T_{BG} = 2.69 \pm 0.09$°K, where the error is the weighted standard deviation in the mean. This statistical error and the error in Eq. (1) are combined to give a total statistical error of ±0.16°K. Including a possible systematic error of −0.05°K to allow for beam spilling around the reflector, we get a final result of

$$T_{BG} = 2.69^{+0.16}_{-0.21}\,°\mathrm{K} \text{ at } \lambda = 3.2 \text{ cm}. \tag{2}$$

At this wavelength the correction to thermodynamic temperature is negligible.

The results of the 1.58-cm runs are shown in Table II. The run made on 1 August 1967 has been assigned zero weight, primarily because the result is 10 standard deviations from the mean. The data indicated that some systematic change took place within the instrument or in the atmosphere while the T_{SKY}-T_{CL} series was in progress.

From other measurements at $\lambda = 1.58$ cm, it was found that $T_{WALL} = 0.21 \pm 0.08$°K, $T_{REFL} = 0.15 \pm 0.05$°K, and $T_{WINDOW} = 0.04 \pm 0.01$°K. Thus,

$$T_{He} + T_{WALL} + T_{WINDOW} - T_{REFL} = 3.87 \pm 0.11\,°\mathrm{K}. \tag{3}$$

The error includes ±0.05°K from uncertainty in tipping angles and ±0.04°K from possible deviation of tip results from the calculated tipping law. A weighted average of the values in column 6 gives $T_{BG} = 2.79 \pm 0.04$°K, where the error is the weighted standard deviation in the mean. Combining this statistical error with the error in Eq. (3) gives a total statistical error of ±0.12°K. Adding the possible systematic error of −0.15°K due to beam spill, we get a final error of $^{+0.12}_{-0.17}$ °K. A correction of −0.01°K is made to convert to thermodynamic temperature, and the final result is

$$T_{BG} = 2.78^{+0.12}_{-0.17}\,°\mathrm{K} \text{ at } \lambda = 1.58 \text{ cm}. \tag{4}$$

For completeness we list the result from Ref. 5:

$$T_{BG} = 2.56^{+0.17}_{-0.22}\,°\mathrm{K} \text{ at } \lambda = 8.56 \text{ mm}. \tag{5}$$

In Fig. 1 the three results are shown on a plot of monochromatic brightness versus wavelength. Shown also is the spectrum of a 2.7°K black body; it peaks at about $\lambda = 2$ mm. Since the above results are in substantial agreement with $T_{BG} = 2.7$°K, they fit this curve quite well. On this plot the spectrum of a hot grey body is a straight line of slope = −2. The dashed line is a greybody spectrum which has been fitted to the two longer wavelength points. This line misses the 8.56-mm result by $2\frac{1}{2}$ standard deviations. We believe that this is good evi-

Table II. The results of all runs made with the 1.58-cm radiometer.

Date	Approx.[a] R. A.	$T_{SKY} - T_{CL}$[b] (°K)	T_{ATM}[b] (°K)	T_{CLR}[b] (°K)	T_{BG}[c] (°K)	Wt.
7/10/67	18:30	1.71 ± 0.05	2.83 ± 0.06	0.03 ± 0.01	2.78	1.00
7/18/67	05:30	2.31 ± 0.15	2.87 ± 0.70	0.03 ± 0.01	3.34	0.14
7/22/67	23:00	2.00 ± 0.03	3.39 ± 0.30	0.02 ± 0.01	2.50	0.35
7/22/67	17:30	4.07 ± 0.08	4.86 ± 0.08	0.02 ± 0.01	3.10	0.71
7/25/67	05:30	3.49 ± 0.05	4.96 ± 0.39	0.02 ± 0.01	2.42	0.27
7/26/67	19:00	3.09 ± 0.11	4.25 ± 0.46	0.02 ± 0.01	2.73	0.21
8/1/67	06:30	4.91 ± 0.13	4.75 ± 0.15	0.02 ± 0.01	4.05	0[d]
8/11/67	19:30	3.66 ± 0.07	4.73 ± 0.11	0.03 ± 0.01	2.83	0.63
8/26/67	06:30	1.96 ± 0.16	3.05 ± 0.60	0.03 ± 0.01	2.81	0.16
8/26/67	23:30	2.91 ± 0.13	4.12 ± 0.06	0.03 ± 0.01	2.69	0.60
8/27/67	02:00	2.92 ± 0.13	4.13 ± 0.07	0.03 ± 0.01	2.69	0.57

[a] Declination = 37° 30'.

[b] Errors are standard deviations in the mean, or limits of drift, whichever is larger.

[c] Not yet corrected to thermodynamic temperature.

[d] Weight assigned on basis of large deviation from mean of T_{BG} for this run.

dence for spectrum curvature, and argues strongly against a hot greybody source.

If one adopts the view that the cosmic microwave background radiation has a blackbody spectrum, the above results can be combined to give an accurate value for the temperature. Averaging the three numbers gives 2.68°K,

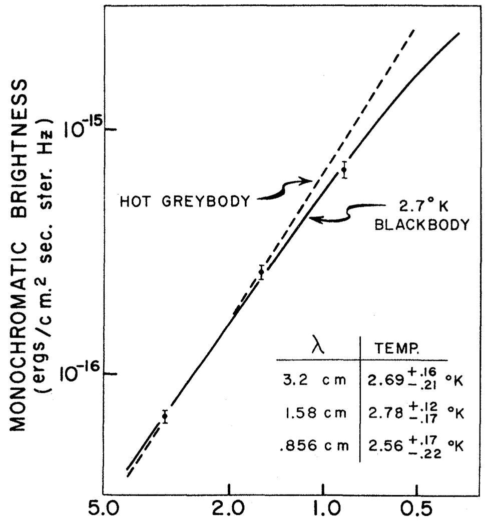

FIG. 1. The results of the measurements reported in this and the preceding Letter.

with a standard deviation of ±0.09°K. Adding in the possible systematic error of −0.05°K, common to all measurements, we get a result of

$$\mathcal{T}_{BG} = 2.68^{+0.09}_{-0.14}\,^{\circ}\mathrm{K}. \tag{6}$$

This result falls within the error limits of all of the radiometer results[2] reported to date.

We would like to thank Dr. Nello Pace for allowing us to use the facilities of the White Mountain Research Station. We are grateful to Dr. Duane Blume, Mr. Bob Delker, and the station staff for many services rendered during our visit. Mr. A. A. Mondelli built and tested the 3.2-cm radiometer as part of his senior thesis work. Finally, we are indebted to Dr. N. J. Woolf for pointing out that the correction for atmospheric absorption of the background radiation is contained in our measurement of $\mathcal{T}_{ATM}$ and does not need to be made separately.

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†Alfred P. Sloan Foundation Fellow.

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EXPERIMENTAL TEST OF ELECTRON-SCATTERING SUM RULES FOR CARBON[*][†]

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The cross section for scattering of electrons off carbon has been measured at laboratory angles of 3.3°, 6°, and 12° for incident energies of 1 to 5 GeV. The measured cross sections are in good agreement with the sum rules describing this process.

In an experiment at the Cambridge Electron Accelerator we have measured the electron-scattering cross section of carbon for incident electron energies between 1 and 5 GeV and at laboratory angles of 3.3°, 6°, and 12°. The purpose of the experiment was to determine the elastic and inelastic carbon form factors so that one could unambiguously analyze the quantum-electrodynamics experiments performed using carbon targets. The results of this experiment agree with the sum rules for electron-carbon scattering.

A half-quadrupole spectrometer was employed to determine the momentum of the electrons. The electrons were identified by a fourfold scintillation counter telescope, a threshold gas Čerenkov counter, and a lead-scintillator shower counter. The acceptance of the system was calculated using a ray tracing program and checked by measuring the known hydrogen cross section. The carbon targets used were 1.1 or 2.2 g/cm^2 thick. The electron beam was monitored with a Faraday cup whose calibration was known to ±2 %.

For each incident energy and scattering angle, the energy spectrum of the scattered electrons was measured from well above the elastic peak to a point well below the elastic peak. The data points were corrected for target-out rates (~7 %), random coincidences (~1 %), dead-time loss (~8 %), Čerenkov and shower counter inefficiency (~0.4 %), and pion contamination (~0.15 %). The statistical error on most of the data points was 1 % or less and is totally negligible when compared with the uncertainties in the corrections.

The energy resolution of the apparatus was insufficient to resolve the elastic scattering, the inelastic scattering involving nuclear excitation, and the quasielastic scattering from protons and neutrons in the carbon nucleus.

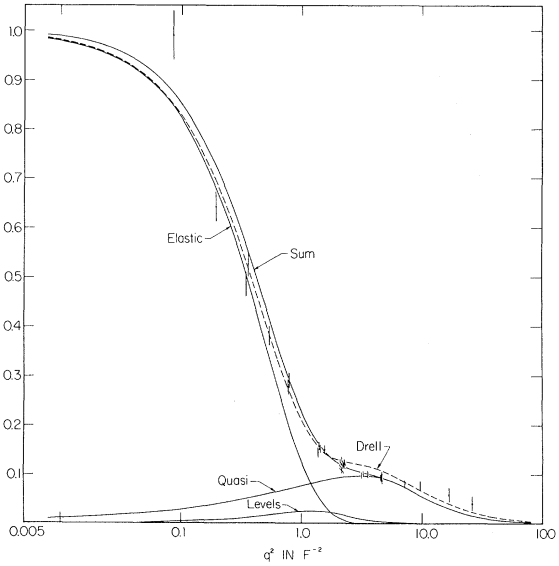

FIG. 1. Experimental and theoretical form factors versus the four-momentum transfer squared. Drell is an evaluation of the sum rule due to Drell and Schwartz, Elastic is the elastic scattering form factor, Levels is the sum of the inelastic scattering with nuclear level excitation form factors, Quasi is the quasielastic scattering form factor, Sum is the sum of Elastic, Levels, and Quasi. The experimental data are shown as points.