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# Cosmic-Ray Bursts and the Nucleonic Cascade*†

G. N. WHYTE
*Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

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The cosmic-ray burst rate has been measured as a function of altitude at geomagnetic latitudes of 0°, 29°, and 35°N by means of a thin-walled spherical ionization chamber. The burst rate at an atmospheric depth of 20 g/cm$^2$ increases by a factor of 6 between 0° and 52°. When the data are corrected for the effects of heavy primary nuclei, the residual rates, believed due almost entirely to nuclear disintegrations, show maxima below the top of the atmosphere. The maxima at 0°, 29°, 35°, and 52° occur at depths of approximately 100, 70, 60, and 50 g/cm$^2$ respectively.

## I. INTRODUCTION

THE establishment of the fact that, at mountain altitudes and above, a thin-walled ionization chamber can be used as a detector of the radiation producing nuclear disintegrations[1,2] has led to the use of such chambers for the investigation of the altitude dependence of this "star-producing" component. The work of Bridge and Rossi[3] at mountain and B-29 altitudes, of Hulsizer,[4] Coor,[5] and McClure and Pomerantz[6] at balloon altitudes, and of Tatel and Van Allen[7] at rocket altitudes gives the variation of the burst rate in thin-walled ion chambers through the entire atmosphere in the neighborhood of 52°N. These results indicate an exponential decrease in the lower atmosphere with an absorption length close to 140 g/cm$^2$, in good agreement with the value for stars in photographic emulsions.[8] At high altitudes the data appear to differ somewhat from the simple absorption of an isotropic primary component,[9] and, in fact, when the rates are corrected for the contribution of heavy primary nuclei,[6,10] they show an initial build-up below the top of the atmosphere.

The purpose of the experiments to be described was to extend the investigation to higher average primary energies by making high altitude burst measurements at lower latitudes. To this end, five balloon flights were made from the *U. S. S. Norton Sound* in the Pacific during the summer of 1949.

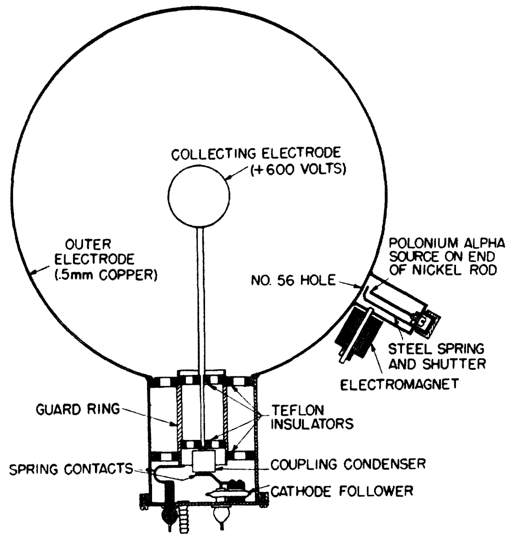


FIG. 1. Cross section through ionization chamber.

## II. EXPERIMENTAL METHOD

The experimental equipment was substantially the same as that used by Coor and described in detail by him.[11] It was comprised of the ion chamber with its associated amplifier and telemetering equipment mounted in a light balloon-borne gondola, and a receiving and recording station on the ship.

The chamber (Fig. 1) consisted of a spherical copper shell, 30 cm in diameter and 0.054 cm in wall thickness,

TABLE I. Schedule of flights. The two flights made by Coor at 52° are included.

| Date | Geographic point of launching | Geomagnetic latitude | Maximum altitude (ft) | g/cm² | Duration (hr) |
|---|---|---|---|---|---|
| July 11, 1949 | 00°11′N 160°03′W | 0° | 103,000 | 9 | 3 |
| July 16, 1949 | 01°30′N 157°30′W | 2° | 95,000 | 14 | 4.7 |
| July 20, 1949 | 00°01′N 158°21′W | 0° | 85,000 | 22 | 7 |
| August 9, 1949 | 27°40′N 148°10′W | 29° | 88,000 | 19 | 6 |
| August 13, 1949 | 30°25′N 129°52′W | 35° | 93,000 | 15 | 9 |
| January 27, 1948 | Princeton, N. J. | 52° | 92,000 | 16 | 3.8 |
| March 1, 1948 | Princeton, N. J. | 52° | 50,000 | 120 | 3.5 |

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1 H. S. Bridge, Phys. Rev. **72**, 172 (1947).
2 Bridge, Hazen, Rossi, and Williams, Phys. Rev. **74**, 1083 (1948).
3 H. S. Bridge and B. Rossi, Phys. Rev. **71**, 379 (1947).
4 R. I. Hulsizer, Phys. Rev. **73**, 1252 (1948).
5 T. Coor, Princeton University thesis (1948), (to be published).
6 G. W. McClure and M. A. Pomerantz, Phys. Rev. **79**, 911 (1950).
7 H. E. Tatel and J. A. Van Allen, Phys. Rev. **73**, 87 (1948).
8 Bernardini, Cortini, and Manfredini, Phys. Rev. **74**, 845 (1948); **74**, 1878 (1948).
9 B. Rossi, Revs. Modern Phys. **20**, 537 (1948).
10 G. N. Whyte, Phys. Rev. **78**, 321 (1950); **78**, 630 (1950).
11 Coor, Snow, and Darago, Rev. Sci. Instr. (to be published).

and a concentric spherical collecting electrode, 5 cm in diameter, maintained at 600 volts positive with respect to the shell. The use of pure argon at 1.4 atmos pressure as the chamber gas permitted electron collection to be employed. Periodic calibration of the over-all response of the system was provided by a polonium source mounted on the chamber; a number of alpha-particles from this source were allowed to dissipate approximately 5.2 Mev each in the gas every 15 minutes. Burst sizes between 0.7 and 20 Po-alpha could be detected.

Pulses due to ionization taking place in the chamber gas were magnified by a linear amplifier (rise time 3 $\mu$sec, decay time 50 $\mu$sec), before being fed to the telemetering circuit. Here they were converted to a form more suitable for transmission and allowed to modulate an audiofrequency signal. A second audiofrequency channel carried pressure information from an aneroid barometer and temperature information from a temperature-sensitive resistor. The two audio channels finally frequency-modulated an rf channel which transmitted the information to the receiving station on the ship. There it was decoded and recorded on a moving strip of photographic paper.

The contents of the gondola were protected from extremes of temperature by a cellophane wrapping, the chamber being shielded from the direct rays of the sun by a layer of aluminum foil. The gondola was lifted by a cluster of Dewey and Almy J-2000 balloons which gave a rate of rise around 500 ft/min to a maximum altitude between 80,000 and 100,000 ft. In some flights data were obtained during the descent as well as the ascent.

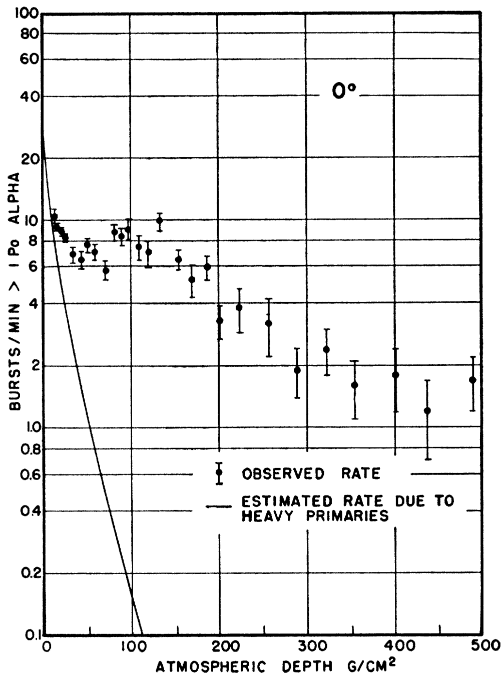

FIG. 2. Burst rate *vs* atmospheric depth at 0° geomagnetic.

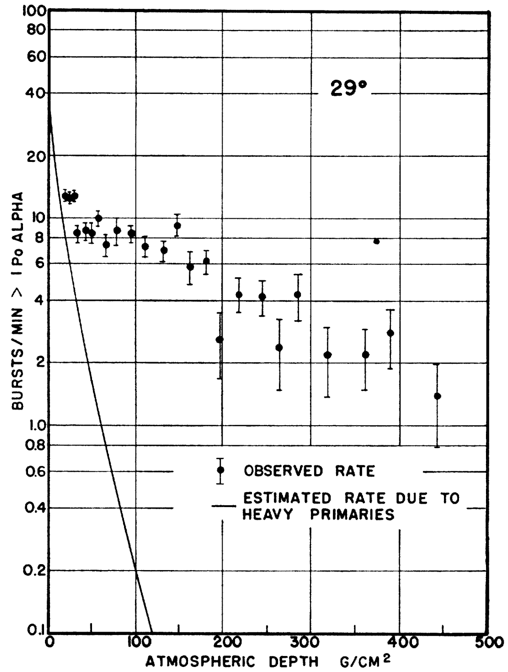

FIG. 3. Burst rate *vs* atmospheric depth at 29° geomagnetic.

## III. EXPERIMENTAL RESULTS

Three flights were carried out at the geomagnetic equator, one at 29°N, and one at 35°N. A summary of information pertaining to these five flights is presented

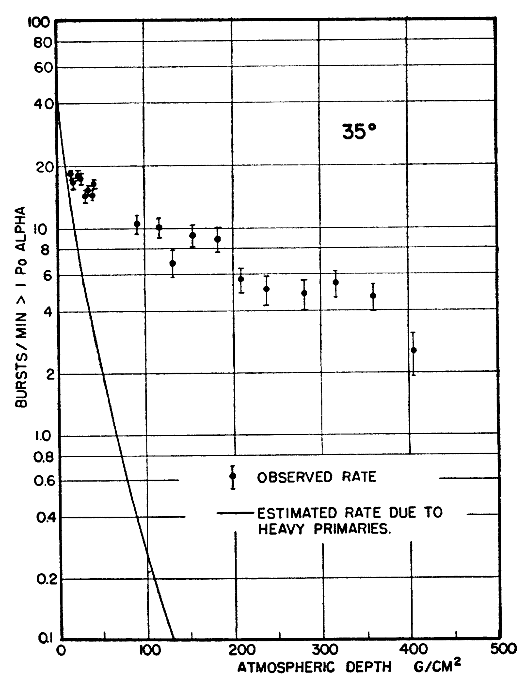

FIG. 4. Burst rate *vs* atmospheric depth at 35° geomagnetic.

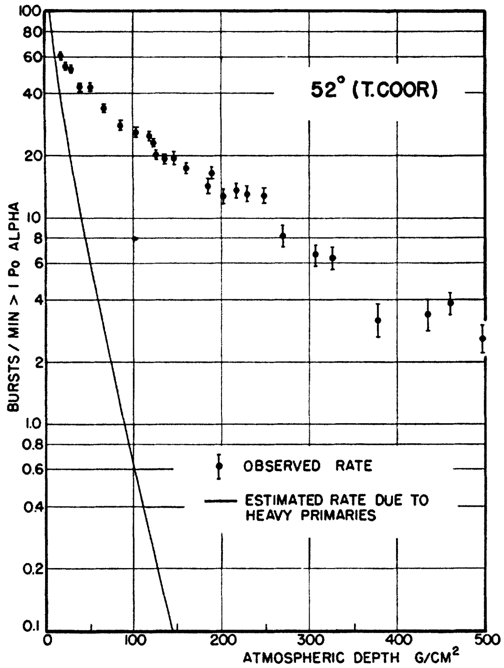


FIG. 5. Burst rate *vs* atmospheric depth at 52° geomagnetic (T. Coor, reference 5).

in Table I, together with the corresponding data for the two flights made with an identical chamber by Coor at 52°.

Figures 2 to 5 show the variation of the burst rate with atmospheric depth. The rates given are for all bursts greater than 1 Po-alpha in size, averaged over one or more 5-min intervals. In the 0°-latitude case the results for the three flights, which show no significant differences, have been averaged together. All rates have been corrected for the background rate at sea level, due principally to alpha-particles from radioactive materials in the chamber walls.

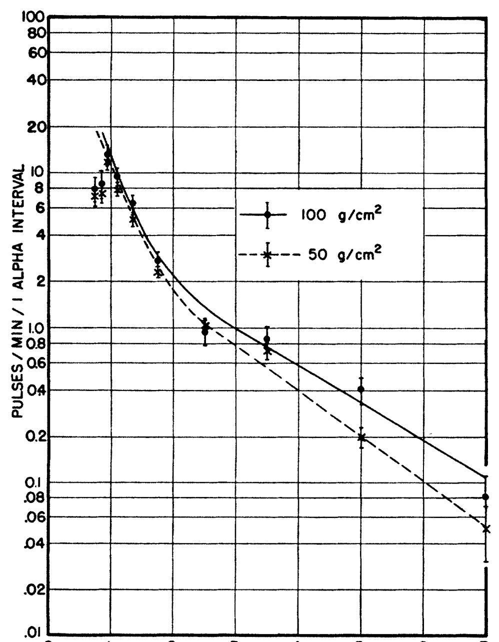


FIG. 6. Comparison of differential pulse size distributions at 50 and 100 g/cm² at 0° geomagnetic.

Despite the poor statistics, the most noticeable feature of Figs. 2 to 5 is the apparent maximum in the burst rate at 0° at a depth of about 100 g/cm². At 29° there appears to be a plateau in this region, while at 35° the data between 40 and 80 g/cm² are uncertain, so that it is difficult to determine the shape of the curve. At 52° there is no sign of either a maximum or a plateau. A check on the sizes of the Po calibration pulses showed that the effect at 0° could not be due to changes

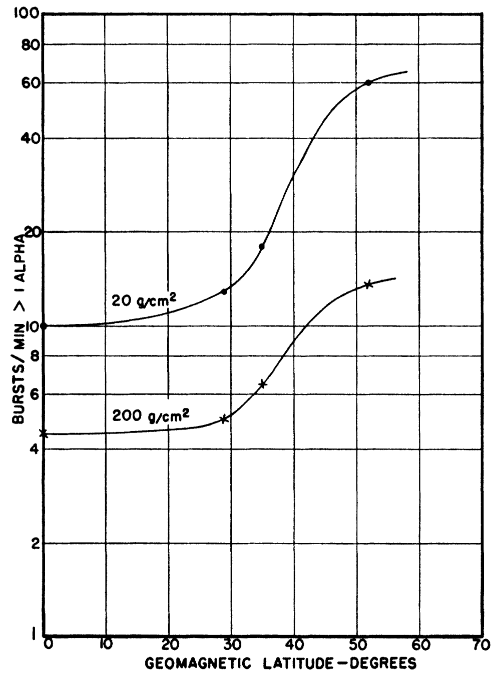


FIG. 7. Latitude variation of burst rate.

in the gain of the equipment, a fact supported by the reproducibility of the results in different flights. Pulse-size distributions plotted around the minimum at 50 g/cm² and around the maximum at 100 g/cm² show that the rate at the latter depth was consistently greater over the range of burst sizes observed (Fig. 6). Thus, the effect cannot be due to spurious pulses of one particular size, nor is it likely to be the result of a statistical fluctuation. The data at the lower latitudes, thus, indicate a real maximum in the cosmic-ray burst rate well below the top of the atmosphere.

Figure 7 shows the latitude variation of the burst rate at two different altitudes. It is of interest to note that at high altitudes (20 g/cm²) the rate increases by a factor of 6 between 0° and 52°, whereas at a depth of 200 g/cm² this factor is only 3.

## IV. DISCUSSION

Three types of phenomenon should be able to produce detectable bursts in the chambers used: electron showers, heavy primary nuclei, and nuclear disintegrations in or near the chamber walls. Of these, the contribution of the first is negligible[1,2,5] and that of the second can be estimated from other measurements; therefore, the rate due to nuclear disintegrations can be found.

In order to estimate the rate due to heavy primary nuclei, one needs to know what charge a relativistic nucleus must have before it can cause a burst greater that 1 Po-alpha by ionization in passing through the chamber. On the assumption that all $\delta$-rays of energies less than about 200 kev dissipate most of their energies in the chamber gas, the Bethe-Bloch formula gives a mean energy loss of 70 kev for singly charged primaries crossing the chamber. (A mean path length through the chamber of 20 cm has been used here.) Taking the energy loss to be proportional to $Z^2$, one finds that primary particles of charge 9 or greater should produce bursts greater than 1 Po-alpha. The flux of such particles at the top of the atmosphere at 52° can be estimated from the measurements of Bradt and Peters[12] to be $0.55\pm0.16\times10^{-3}$ nuclei cm$^{-2}$ sec$^{-1}$ sterad$^{-1}$; the resulting burst rate is 150/min. Assuming isotropic incidence, so that the variation with depth, $t$, is of the form $N(t)=N(0)[e^{-t/L}+E_i(-t/L)]$, and using for $L$ the collision mean free paths measured as a function of charge by Bradt and Peters, one arrives at the curve of burst rate *vs* altitude shown in Fig. 5 (solid line). From the preliminary energy spectrum for heavy primaries calculated by Vallarta[13] and the geomagnetic cut-off energies[14,15] at 0°, 29°, and 35°, one can now estimate the heavy-primary fluxes at these latitudes and thence obtain the corresponding curves of burst rate *vs* altitude. These are shown in Figs. 2, 3, and 4.

It may be worth emphasizing that the burst rates just calculated arise from particles of such high specific ionization that they cause bursts greater than 1 Po-alpha simply in passing through the chamber. Such particles are detected with 100 percent efficiency, in contrast to ordinary star-producing particles which are detected with an efficiency of the order of 1 percent. Thus, at the altitudes where heavy primaries exist in appreciable numbers their contribution to the burst rate is disproportionately large.

The results of subtracting the estimated heavy primary rates from the observed total rates are shown in Figs. 8 to 11. (The errors shown include the statistical errors in the burst measurements and in the heavy-primary fluxes, and an estimate of the possible error due to approximations in the calculation of the heavy-primary rates.) The burst rate now exhibits a maximum at all latitudes, the position of this maximum being nearer the top of the atmosphere at higher latitudes. The depths of the maxima at 0°, 29°, 35°, and 52° respectively are approximately 100, 70, 60, and 50 g/cm². Because of the rather large uncertainties in the heavy-particle correction, these positions become progres-

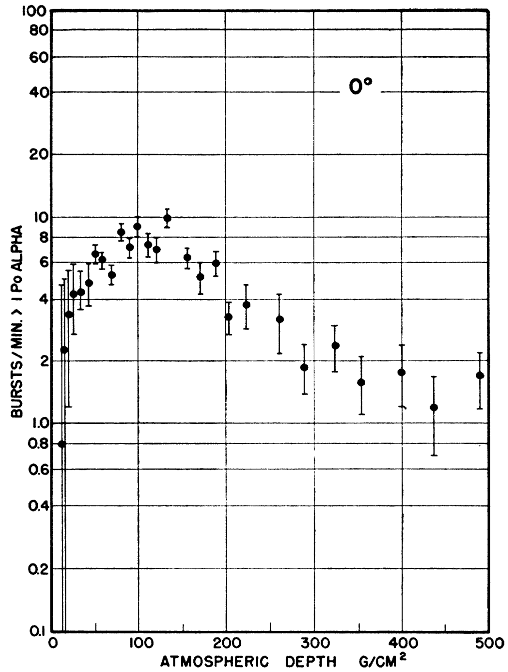


FIG. 8. Nuclear disintegration rate *vs* atmospheric depth at 0° geomagnetic.

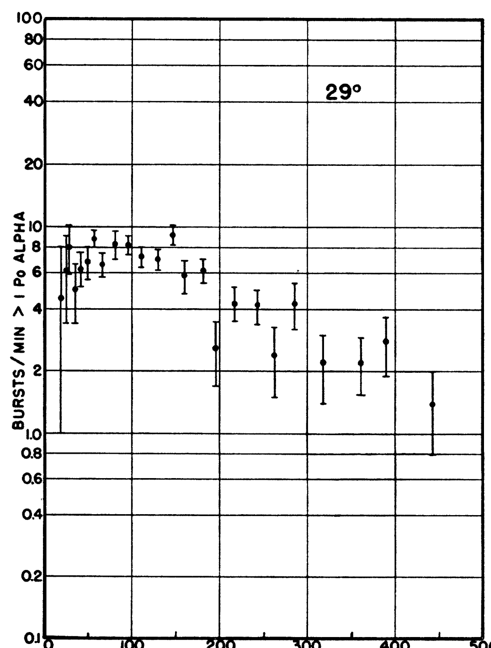


FIG. 9. Nuclear disintegration rate *vs* atmospheric depth at 29° geomagnetic.

[12] H. L. Bradt and B. Peters, Phys. Rev. 77, 54 (1950).
[13] M. S. Vallarta, Phys. Rev. 77, 419 (1950).
[14] M. S. Vallarta, Phys. Rev. 74, 1837 (1948).
[15] G. Lemaitre and M. S. Vallarta, Phys. Rev. 43, 87 (1933).

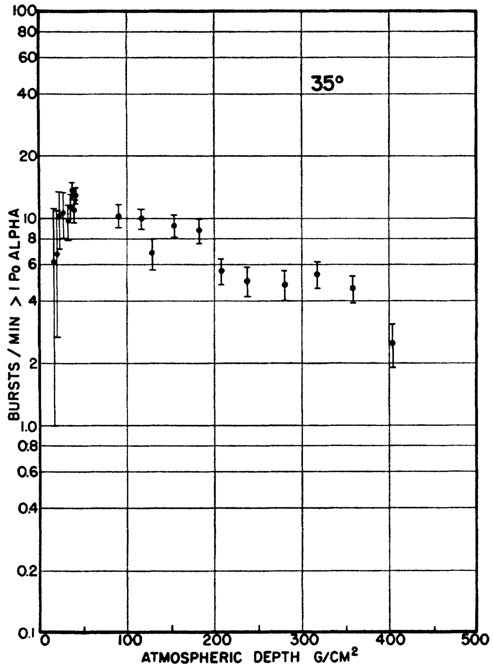


FIG. 10. Nuclear disintegration rate *vs* atmospheric depth at 35° geomagnetic.

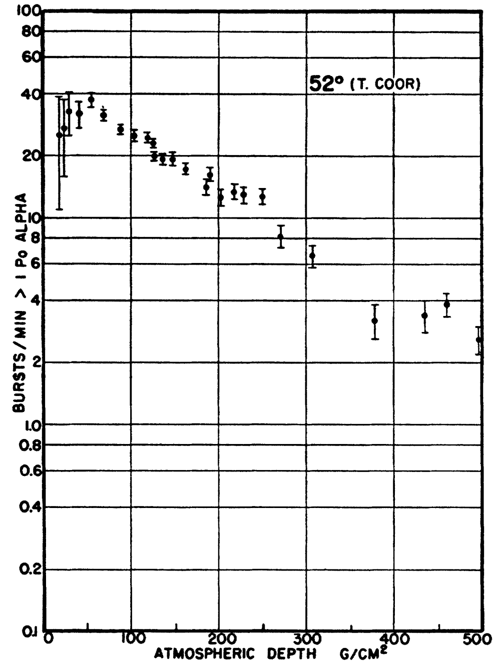


FIG. 11. Nuclear disintegration rate *vs* atmospheric depth at 52° geomagnetic.

sively less well defined with increasing latitude, until at 52° the data are not inconsistent with a mere leveling off of the star rate at the top of the atmosphere. On the other hand, the maximum at 0° appears even before the heavy-particle correction is made, so that its position depends but slightly on that correction.

These results indicate strongly that a large fraction of the nuclear disintegrations capable of producing bursts in a thin-walled ion chamber are initiated by secondary particles which multiply in the atmosphere by a cascade process. Since $\pi$-mesons travel a negligible fraction of a mean free path in air before decaying, these secondary particles are presumably nucleons.

The variation of latitude effect with atmospheric depth now finds a ready explanation. At very high altitudes the cascade has not had a chance to develop fully; the increase by a factor of 6 between 0° and 52° is comparable to that of the primaries.[16] At a depth of 200 g/cm² the primaries at the equator, possessing higher average energies than those farther north, have given rise to more secondaries through a longer cascade; the increase between 0° and 52° is only 3. This latter value is comparable to that found for bursts and fast neutrons at 300 g/cm² by Simpson[17] and rather less than that found by Yuan[18] for slow neutrons. It provides another indication of the close connection between bursts and the nucleonic component.

A comparison of these results with nucleonic cascade theory will be made in a forthcoming paper by S. Schweber and A. S. Wightman.

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[16] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[17] J. A. Simpson and R. B. Uretz, Phys. Rev. **76**, 569 (1949); J. A. Simpson and E. Hungerford, Phys. Rev. **77**, 847 (1950).

[18] L. C. L. Yuan, Phys. Rev. **78**, 325 (1950).