

Measurement of Low-Energy Cosmic-Ray Protons*

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The results of a high-altitude balloon measurement of the primary-proton spectrum at energies between 57 and 77 MeV are reported. It is concluded that the primary flux of these low-energy protons at Churchill is negligible, both as compared to the atmospheric secondary contribution and as compared to the primary flux at higher (~ 1 BeV) energies. A statistical upper limit of $dJ/dE < 0.49$ protons/m²-sr-sec-MeV at $E \cong 67$ MeV is obtained.

INTRODUCTION

TO understand the solar modulation of the galactic beam and the solar acceleration of cosmic-ray particles, both primarily lower energy phenomena, a thorough knowledge of the cosmic-ray differential energy spectrum at low energies is fundamental. Until recently, definitive experimental data has been lacking due to the difficulties encountered in low-energy particle measurements. The available information has been largely of a speculative nature.

A series of balloon flights by Winckler and Anderson¹ in 1955 found evidence based upon altitude and latitude considerations that could be interpreted as implying a substantial flux of low-energy particles. It has also been suggested by Simpson² that the sun may continuously emit low-energy particles in appreciable numbers. On the other hand, a very accurate differential flux measurement made by McDonald and Webber³ near solar minimum in 1955 would, if extrapolated to lower energies, imply an inappreciable flux of low-energy protons. A direct measurement of the proton spectrum by Vogt⁴ in 1960 reportedly detected substantial numbers of primary protons in the energy region around 100 MeV. Considered here are the results of a measurement at primary proton energies between 57 and 77 MeV.

PROCEDURE

The principal difficulty encountered in measuring primary low-energy protons with a balloon-borne detector is the atmospheric secondary contribution. The procedure adopted was to make use of the geomagnetic cutoff to separate primaries from atmospheric secondaries. This was accomplished by flying identical detectors at two sites: Churchill, Manitoba and Sioux Falls, South Dakota. At Churchill, the vertical cutoff

for protons is 21 MeV, and for deuterons 10.5 MeV.^{5,6} From the same references, the vertical cutoffs at Sioux Falls are approximately 740 MeV for protons and 460 MeV for deuterons. Since the primary cosmic-ray particles of interest are protons of about 70 MeV and deuterons of about 85 MeV, it is clear that in the vertical direction, the primary particles if present should be seen at Churchill and should not be seen at Sioux Falls. However, the atmospheric secondaries will be present at both locations. Moreover, the atmospheric secondaries will be present in nearly the same amount at both locations in spite of the difference in geomagnetic cutoff. This conclusion is arrived at upon examination of an integral spectrum obtained by McDonald and Webber⁷ which shows that due to the shape of the primary beam's differential spectrum, approximately 90 percent of the total cosmic-ray intensity seen at zero cutoff should be seen at a cutoff corresponding to that of Sioux Falls. Then at Churchill, a balloon-borne detector should see the primary particles in the energy region of interest plus the atmospheric secondaries, while at Sioux Falls, only the atmospheric secondaries should be seen. Upon subtracting the Sioux Falls counting rate from the Churchill counting rate, one should obtain the cosmic-ray primary counting rate from which the primary flux may be found.

This straightforward approach to the atmospheric secondary problem is complicated by the re-entrant

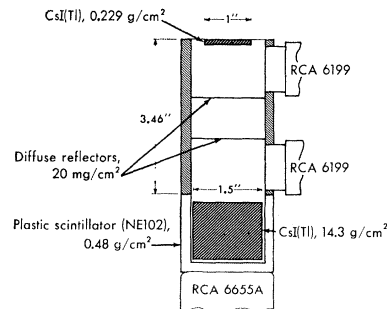


FIG. 1. Detector in cross section.

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¹ J. Winckler and K. Anderson, *Phys. Rev.* **108**, 148 (1957).

² J. A. Simpson, *Astrophys. J., Suppl.* **4**, No. 44, 378 (1960).

³ F. B. McDonald and W. R. Webber, *Phys. Rev.* **115**, 194 (1959).

⁴ R. Vogt, *Phys. Rev.* **125**, 366 (1962).

⁵ J. J. Quenby and G. J. Wenk, *Phil. Mag.* **7**, 1457 (1962).

⁶ H. H. Sauer, *J. Geophys. Res.* **68**, 957 (1963).

⁷ F. B. McDonald and W. R. Webber, *Goddard Space Flight Center Contributions to 1961 Kyoto Conference on Cosmic Rays and the Earth Storm, Greenbelt, Maryland, 1961* (unpublished).

albedo effect. As pointed out by Treiman,⁸ the re-entrant albedo contribution may be significant for particle rigidities below the local geomagnetic cutoff. Then at Sioux Falls, these re-entrant albedo particles should be seen as well as the atmospheric secondaries. At Churchill, any re-entrant albedo must be below the geomagnetic cutoff and so cannot affect the measured energy interval. In summary, the differential fluxes to be expected at the two locations are:

at Churchill,

$$\left(\frac{dJ}{dE}\right)_{\text{total}} = \left(\frac{dJ}{dE}\right)_{\text{galactic+solar}} + \left(\frac{dJ}{dE}\right)_{\text{secondary}};$$

at Sioux Falls,

$$\left(\frac{dJ}{dE}\right)_{\text{total}} = \left(\frac{dJ}{dE}\right)_{\text{secondary}} + \left(\frac{dJ}{dE}\right)_{\text{re-entrant albedo}},$$

where the quantities are to be evaluated at appropriate energies.

To justify the approach of subtracting the Sioux Falls flux from the Churchill flux, it is necessary to show that the re-entrant albedo is negligible as compared to the atmospheric secondary flux at balloon altitudes. A theoretical calculation of this re-entrant albedo effect has been performed by Ray.⁹ Ray obtains a value appropriate to Sioux Falls of

$$\left(\frac{dJ}{dE}\right)_{\text{re-entrant albedo}} = 1.17 \text{ protons/m}^2\text{-sr-sec-MeV}$$

at 85 MeV. Looking ahead to the experimental data, there was obtained an uncorrected measured proton flux at Sioux Falls at a residual atmospheric depth of 5.5 g/cm² of

$$\left(\frac{dJ}{dE}\right)_{\text{total}} = 1.61 \pm 0.43 \text{ protons/m}^2\text{-sr-sec-MeV}$$

at 87 MeV, and an uncorrected measured proton flux at Churchill of

$$\left(\frac{dJ}{dE}\right)_{\text{total}} = 1.22 \pm 0.18 \text{ protons/m}^2\text{-sr-sec-MeV}$$

at 67 MeV and a residual depth of 3.0 g/cm². This would seem to imply that the re-entrant albedo is the major contribution at Sioux Falls. It would further imply that the atmospheric secondary flux is negligible at Churchill also and that the proton flux at Churchill is predominantly composed of primary particles.

The results of the experiment under consideration

here indicate that these conclusions are incorrect and that both at Churchill and Sioux Falls the particles seen at these low energies are atmospheric secondaries. Although the experimental data will show this to be the case, a discussion of Ray's theoretical re-entrant albedo calculation is perhaps in order. Using a transport equation describing the motion of protons in a magnetic field, and losing energy due to ionization loss in an atmosphere, Ray arrives at a solution for the proton flux leaving the atmosphere in the upward direction. Assuming the protons travel up out of the atmosphere along the local geomagnetic field line, a re-entrant albedo flux is arrived at. The calculation appears to be oversimplified in two respects: (1) Re-entrant albedo particles are taken to be originating at atmospheric depths of up to 200 g/cm². The only attenuation effect on this upward moving beam which is considered is the degradation in energy through ionization losses. Since the nuclear interaction length for protons in air is about 80 g/cm²,¹⁰ by neglecting the attenuation due to nuclear interactions, a significant error may have been made. (2) To facilitate the performing of the integral which is obtained for the differential re-entrant albedo intensity, a mathematical approximation is made that all upward moving albedo particles move along the local field lines. This approximation is physically equivalent to allowing all secondary particles emitted in any direction in the upper hemisphere to proceed precisely along the local field line with no spiraling. Since the geomagnetic field lines are nearly vertical at the southern latitude conjugate to Sioux Falls, the particles are then assumed to travel upward through a minimum residual atmosphere. In reality, the bulk of the upward-emitted secondary particles are emitted at large zenith angles. The net effect of the approximation is then to allow all upward-emitted secondary particles to proceed directly out of the atmosphere through the shortest possible layer of residual air. This then permits the re-entrant albedo particle to start out with a lower energy. If, for example, the particle is to emerge from the atmosphere with an energy of E MeV, then it must start out with a somewhat higher energy due to the ionization losses it will suffer. Allowing the particle to pass through too thin an atmospheric layer is equivalent to allowing it to start out with too low an initial energy. Due to the energy spectrum of the secondary particles,¹¹ this results in an over-estimate of the re-entrant albedo flux. This under-estimate of the amount of atmosphere that the particles must pass through greatly aggravates the omission of nuclear interactions discussed in (1). The net result of these two errors is that the value of the theoretical re-entrant albedo flux arrived at by Ray is considerably too large. It therefore seems likely that the re-entrant albedo flux in the region of 100-MeV proton energy is

¹⁰ W. D. Walker, S. P. Walker, and K. Greisen, *Phys. Rev.* **80**, 546 (1950).

¹¹ U. Camerini, P. H. Fowler, W. O. Lock, and H. Muirhead, *Phil. Mag.* **41**, 413 (1950).

⁸ S. B. Treiman, *Phys. Rev.* **91**, 957 (1953).

⁹ E. Ray, *J. Geophys. Res.* **67**, 3289 (1962).

small or negligible compared to the locally-produced secondary flux. The experimental data presented here show this to be the case.

INSTRUMENTATION

The immediate goal of the experiment was to make a precise measurement of the primary proton flux over a relatively narrow energy interval at as low an energy as possible.

The technique utilized to detect and identify the particles was to make dE/dx and total-energy measurements on each particle. Such measurements serve to identify the type of particle as well as to measure its energy. For this purpose three optically separate scintillation phosphors were used. The detector is shown in cross section in Fig. 1. The top thin crystal, viewed only by the top photomultiplier tube, made the dE/dx measurement. The total-kinetic-energy measurement was made by the lower cesium iodide crystal viewed only by the lower RCA 6199 tube. In addition there was a plastic phosphor, optically sealed from the total energy crystal, which was viewed by the RCA 6655A tube. By a coincidence-anticoincidence arrangement, acceptable particles were required to pass through the top crystal and stop in the lower crystal. Pulse-height information from the two cesium iodide crystals was telemetered and recorded in digital form at the ground receiving station. The instruments were individually calibrated, and with the aid of range-energy relationships it was possible to identify each particle event as to type of particle and total energy.

FLIGHT INFORMATION AND DATA

The work presented here is based on the results of two balloon flights. The Churchill flight, conducted on 10 and 11 August 1962, utilized a 3 million cubic foot balloon and yielded 481 minutes of usable data at a floating altitude equivalent to an effective depth of 3.0 g/cm^2 . The Sioux Falls flight, conducted on 5 November 1962, utilized a 1 million cubic foot balloon and yielded 138 minutes of data at an effective depth of 5.5 g/cm^2 . The Sioux Falls flight was shortened by high-speed winds at balloon altitude.

Both flights were made during periods unlikely to show any solar influence beyond the overall modulation of the cosmic ray beam expected at this phase of the solar cycle. Specifically, no solar cosmic ray events or Forbush decreases were in progress.¹²

In the summarized results of the two flights presented below, the deuterons and tritons are grouped together to improve statistics and to facilitate comparison with other data to be discussed later. The raw data are shown in Figs. 2 and 3.

¹² Solar-Geophysical Data, U. S. Department of Commerce, National Bureau of Standards, Central Radio Propagation Laboratory Boulder, Colorado, August–November 1962 (unpublished).

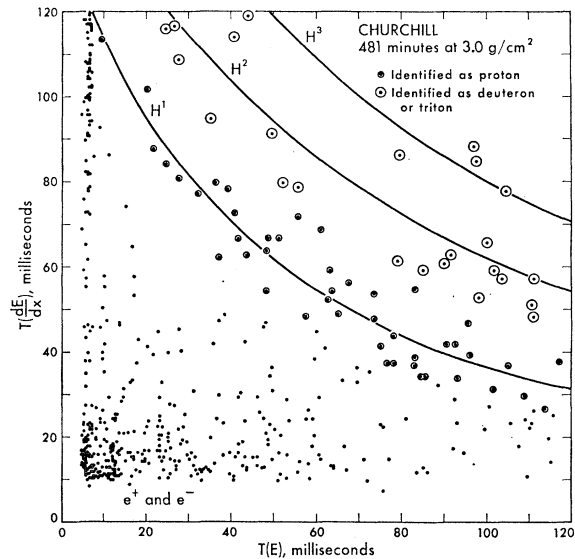


FIG. 2. Curves labeled H^1 , H^2 , H^3 are curves to be expected on basis of calibration and range-energy relationships. Pulse durations in milliseconds are related to energy losses in MeV by the relations

$$\begin{aligned} T(E) &= aE + b \\ T(dE/dx) &= c\Delta E + d. \end{aligned}$$

The spread in the electrons is due principally to statistical fluctuations in their energy losses. The spreads in the protons, deuterons, and tritons are due principally to the resolution limitations of the detector. The resolution of each CsI(Tl) crystal-photomultiplier tube combination was approximately 10% full width at half-maximum. [Exposure: 481 min at 3.0 g/cm^2 .]

ANALYSIS

One of the most significant measurements reported here is the isotopic abundance of the $Z=1$ flux at these low energies. This measurement, in principle, can give much more discriminating information on the origin of these particles than can a gross measurement of the $Z=1$ components taken together. The measured values of the ratio $R = (H^2 + H^3)/(H^1 + H^2 + H^3)$ are

$$\begin{aligned} \text{Churchill} & 0.35 \pm 0.08 \\ \text{Sioux Falls} & 0.36 \pm 0.15, \end{aligned}$$

where the errors are standard deviations. The similarity in the isotopic abundance ratios at both locations is evidence that the particles have the same origin. The only source of these particles common to both Churchill and Sioux Falls is the atmospheric secondary flux. If we make the assumption that the near equality of the abundance ratios at both sites means a common origin, then we are immediately led to the conclusion that the great preponderance of particles sampled were of atmospheric secondary origin. The alternative to the above assumption would be to adopt the viewpoint that this near equality of the isotopic abundance ratios is coincidental. This would imply that the galactic plus solar flux viewed at Churchill had the same isotopic composition as the re-entrant albedo flux viewed at

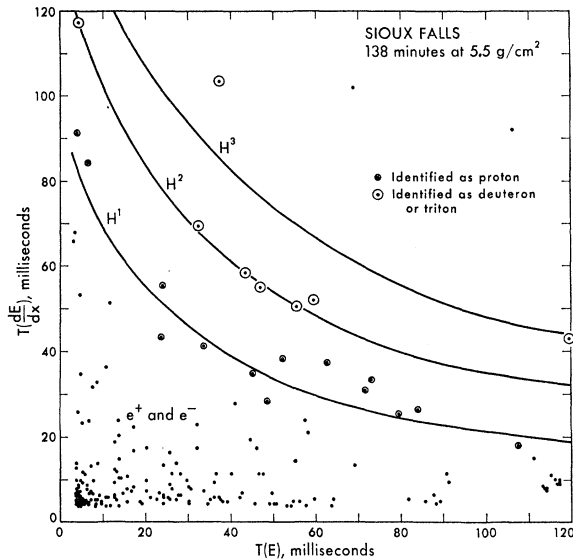


FIG. 3. Same as Fig. 2 but Exposure: 138 min at 5.5 g/cm².

Churchill, 10, 11 August 1962, 481 min, 3.0 g/cm ²	
particle	number of counts
protons	45
deuterons and tritons	24
Sioux Falls, 5 November 1962, 138 min, 5.5 g/cm ²	
particle	number of counts
protons	14
deuterons and tritons	8

Sioux Falls. Although not impossible, the likelihood appears quite small that cosmic-ray hydrogen of solar or galactic origin should have the same isotopic composition as the hydrogen originating in nuclear interactions in the southern hemisphere. This argument is further strengthened by the results of a recent nuclear emulsion measurement by Appa Rao and Lavakare.¹³ They find no evidence for deuterons or tritons in the galactic cosmic-ray beam at higher energies where protons are quite abundant. As also pointed out by these authors, a search by Greenstein¹⁴ for He³ in the sun yielded data which can be interpreted to give an upper limit for solar deuterium which is far lower than the observed abundance quoted above. The conclusion that must be drawn is that the observed abundance ratios considered in the measurements reported here are totally unlike the ratios expected for cosmic-ray hydrogen of solar or galactic origin. However, the observed ratios are typical of those of secondary particles. Powell, Fowler, and Perkins¹⁵ state that $R = (H^2 + H^3) / (H^1 + H^2 + H^3) \cong 0.30$ for secondary particles of approximately 50 MeV resulting from cosmic-ray interactions in nuclear emulsion. An accelerator experiment by Deutsch¹⁶ utilizing 332-MeV protons on various targets

¹³ M. V. K. Appa Rao and P. J. Lavakare, *Nuovo Cimento* **26**, 740 (1962).

¹⁴ J. Greenstein, *Astrophys. J.* **113**, 531 (1951).

¹⁵ C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (Pergamon Press, Inc., New York, 1959).

¹⁶ R. W. Deutsch, *Phys. Rev.* **97**, 1110 (1955).

can be interpreted to show a trend towards higher values of R for lighter target nuclei, explaining the small difference in the values of the observed R and the nuclear emulsion R of Ref. 15. Two other accelerator experiments of interest here gave $R = 0.34$ for 300-MeV neutrons on oxygen¹⁷ and $H^2 / (H^1 + H^2) \cong 0.33$ for 90-MeV neutrons on carbon.¹⁸

The theoretical work by Ray and the observed isotopic abundance ratios are taken as justification for considering the re-entrant albedo a negligible effect. As stated, the observed isotopic abundance ratios are a strong argument for the fluxes being predominantly due to atmospheric secondaries. To obtain a quantitative result for the primary flux, the secondary correction is made by the aforementioned subtraction. The difficulty which is introduced by the difference in altitude between the flights is overcome by using a method previously employed to correct for atmospheric secondaries.¹⁹ A theoretical calculation of the atmospheric secondary flux as a function of altitude is made and then normalized at an altitude where it is known that the flux is predominantly atmospheric secondaries. The normalized calculation can then be subtracted from the measurement made at the altitude of interest leaving the primary flux as remainder.

The atmospheric secondary calculation is described as follows: For a detector viewing a narrow solid angle in the zenith direction, it is easily shown that the secondary flux received from a given thin layer of atmosphere is numerically equal to the production rate in particles per cm²-sec-sr projected vertically downward. The approach to the problem was then to calculate the flux contribution from small increments of atmospheric thickness and then to sum these contributions. In integral form this may be written

$$J(X_0) = \int_0^{X_0} dX \int_{2\pi} d\Omega f(X) \frac{dI(X, \theta)}{dX} p(\theta),$$

$J(X_0)$ being the secondary flux at depth X_0 and at energies acceptable to the detector, where X = atmospheric depth in g/cm². $dI(X, \theta)$ = number of nuclear interactions per cm², per second, in a layer of atmosphere dX thick lying at depth X , the interactions being due to the primary beam within one steradian at θ from the vertical, $f(X)$ = number of secondary particles per interaction, at depth X , which have the proper energy to be accepted by the detector, $p(\theta)$ = the fraction of these $f(X)$ projected vertically downward per steradian when the primary which produced the interaction arrived at θ from the vertical.

Analytic expressions for $dI(X, \theta)$ and $p(\theta)$ were adopted based on nuclear emulsion data. $f(X)$ values

¹⁷ M. O. Fuller, University of California, Lawrence Radiation Laboratory Report UCRL 2699, 1954 (unpublished).

¹⁸ J. Hadly and H. York, *Phys. Rev.* **80**, 345 (1950).

¹⁹ See, e.g., P. Meyer and R. Vogt, *Phys. Rev. Letters* **6**, 193 (1961).

were calculated for depths in increments of 0.25 g/cm^2 based on nuclear emulsion data and range-energy relationships. The integrations were then performed using the IBM-7090 computer at the University of California Computer Center.

Any atmospheric secondary calculation must necessarily be rather strongly dependent upon portions of the input data. Since the applicability of these data must be somewhat doubtful, it is not felt that the absolute magnitudes of the calculated results prior to normalization are sufficiently reliable to be acceptable as a method of correction. The values arrived at prior to normalization for the expected numbers of secondary counts are tabulated below, however, as a matter of interest.

	Sioux Falls, 138 min at 5.5 g/cm^2	
	<i>particle</i>	<i>secondaries expected</i>
protons		16
deuterons and tritons		6
	Churchill, 481 min at 3.0 g/cm^2	
	<i>particle</i>	<i>secondaries expected</i>
protons		50
deuterons and tritons		18.

The unnormalized calculation is seen to be not in disagreement with the conclusion that the particles observed were atmospheric secondaries.

The calculation, as stated earlier, was used merely as a tool to compare two flights at different altitudes. For the purpose of making comparison with the earlier work by Vogt, all protons, deuterons, and tritons were grouped together and considered to be protons. The subtraction of the Sioux Falls flux (corrected for the difference in altitude), from the Churchill flux, yields

$$dJ/dP < 0.18 \text{ particles/m}^2\text{-sr-sec-MV}$$

at $P \cong 360 \text{ MV}$

in terms of rigidity. The result is to be interpreted as implying a negligible flux of primary protons, the upper limit being statistical.

CONCLUSION

The experimental result may be summarized by the statement that on 10 and 11 August 1962, any flux of cosmic-ray protons viewed at a residual depth of 3 g/cm^2 was negligible as compared to the atmospheric secondary contribution. As previously discussed, this result is in disagreement with measurements made by Vogt in 1960. It is shown graphically in Fig. 4 along with a measurement made by McDonald and Webber (Ref. 3) when the sun was at a phase in its 11-yr cycle similar to that of 1962. It is to be emphasized that the result of the experiment under discussion here is consistent with a negligible flux of these low-energy protons.

It is important to consider the possibility that this low-energy portion of the spectrum undergoes a marked time variation. It is, of course, quite possible that large fluctuations due to solar influence could exist. The great fluxes of these lower energy protons seen on

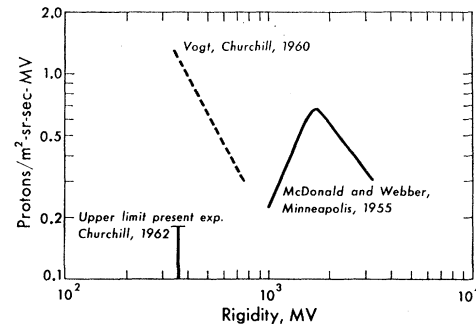


FIG. 4. Summary of proton differential rigidity flux measurements.

occasion in conjunction with large solar flares have been known for years.²⁰ That time dependence will not resolve the difference between the conclusions reached by Ref. 4 and this discussion can best be illustrated by further consideration of the work presented in Ref. 4. The correction for atmospheric secondaries was based on a calculation using nuclear emulsion data. The calculation yielded an atmospheric secondary correction which amounted to the order of 20% of the observed flux at the lowest energies observed. A flight at Churchill on 22 August 1960 at a residual depth of 4.0 g/cm^2 yielded a reported primary flux of

$$dJ/dE \cong 2.0 \text{ protons/m}^2\text{-sr-sec-MeV}$$

at $E \cong 90 \text{ MeV}$.

By assuming for the moment negligible atmospheric secondaries and again grouping protons, deuterons, and tritons together, calling them protons, fluxes may be obtained from the experiment discussed here for purposes of comparison. In this manner, the following fluxes are obtained:

Churchill, 10 and 11 August 1962, 3.0 g/cm^2

$$dJ/dE = 1.87 \pm 0.22 \text{ protons/m}^2\text{-sr-sec-MeV}$$

at $E \cong 67 \text{ MeV}$,

Sioux Falls, 5 November 1962, 5.5 g/cm^2

$$dJ/dE = 2.53 \pm 0.54 \text{ protons/m}^2\text{-sr-sec-MeV}$$

at $E \cong 87 \text{ MeV}$.

Viewed in this manner, the two experiments seem to be in agreement, the disagreement lying wholly in the atmospheric secondary correction. The difference in this correction, approximately 20 percent used in Ref. 4 and the approximate 100 percent arrived at here, of course, leads to quite divergent conclusions.

Further measurements by Vogt and Meyer in 1961²¹ and by McDonald, Ludwig, and Bryant²² in 1961 and

²⁰ K. A. Anderson, R. Arnoldy, R. Hoffman, L. Peterson, and J. R. Winckler, *J. Geophys. Res.* **64**, 1133 (1959).

²¹ P. Meyer and R. Vogt, *Phys. Rev.* **129**, 2275 (1963).

²² D. A. Bryant (private communication, 1963).

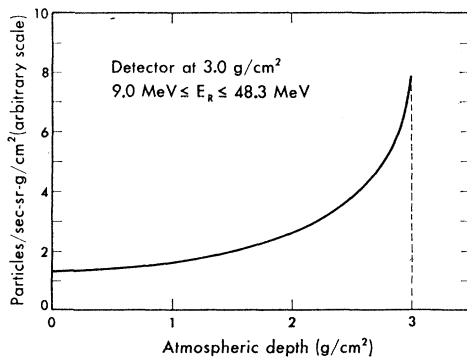


FIG. 5. Atmospheric secondary contribution as a function of residual depth.

1962 yielded uncorrected fluxes which are again in reasonable agreement with the Churchill values quoted above. A little consideration makes it appear unlikely that the small differences in energy or the difference in time of execution of these measurements can explain the difference in conclusions.

It is felt that further attempts to measure the low-energy proton flux at balloon altitudes even as high as 1 g/cm^2 can yield nothing except an upper limit, perhaps somewhat lower than the one arrived at here by gathering sufficient data to improve the statistics. This conclusion is based upon the secondary calculation which shows that the majority of the secondary particles come from interactions in the residual atmosphere closest to the detector. This is illustrated by Fig. 5. The area under the curve is the theoretical flux of secondary protons with residual energies between 9.0 and 48.3 MeV, the detector floating at 3.0 g/cm^2 . The curve is then dJ/dx , the flux contribution as a function of atmospheric depth. By flying this detector at the extreme altitude of 2.0 g/cm^2 , the area between 0 g/cm^2 and 1.0 g/cm^2 is removed. It is seen that such an increase in altitude will not produce an appreciable change in the secondary flux. An equivalent statement is that the altitude versus intensity curve is rather flat until perhaps the last 1.0 g/cm^2 where it begins to fall off steeply. There are two implications here: first, extreme care must be exercised in the extrapolation of observed fluxes to the top of the atmosphere; second, as stated

previously, it appears impossible to obtain more than an upper limit at any feasible balloon altitude.

The obvious solution to obtaining a better measurement is with a satellite-borne detector. However, any such measurement undertaken must have carefully conceived anticoincidence requirements in view of the very low expected flux value. This reasoning has bearing upon a measurement made at somewhat higher energies by a detector aboard Explorer XII.²³ Any confusion due to the Landau spread of higher energy particles or due to nuclear interactions in the satellite material or detector itself makes obtaining of credible data difficult.

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²³ D. A. Bryant, T. L. Cline, U. D. Desai, and F. B. McDonald, *J. Geophys. Res.* **67**, 4983 (1962).