A SEARCH FOR HIGH ENERGY SOLAR NEUTRONS

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by

DAVID J. FORREST
B.S., Lowell Technological Institute, 1963

A THESIS

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This thesis has been examined and approved.

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ABSTRACT

A SEARCH FOR HIGH ENERGY SOLAR NEUTRONS

by

DAVID J. FORREST

An experiment has been performed to search for a flux of solar neutrons at the earth. The detector used was a large plastic scintillator sensitive to neutrons between 20 and 120 MeV. This detector was carried three different times during 1967 and 1968, by balloon, to an atmospheric depth of -4g/cm². The balloons were normally flown through sunrise and as long as possible into the day. By comparison of the day and night counting rates we have deduced that the upper limit for the continuous emission of solar neutrons at the earth is less than $2 \times 10^{-2}$ neutrons/cm² sec in the above energy region. If neutrons were emitted in association with any of the fifteen small flares (of optical importance 1F to 2N) that occurred during the flights, then the maximum flux at the earth was less than $4 \times 10^{-2}$ neutrons/cm² sec. Using a theoretical form we have expressed these results as an upper limit differential solar neutron flux at the earth. The minimum detectable flux with the present instrument is well below the predicted flux from larger flares (e.g., November 12, 1960) of 5 to 50 neutrons/cm² sec.
SECTION I

INTRODUCTION

1. Experimental Objectives

One of the more interesting properties of the sun is its ability to periodically accelerate some of its residual atmosphere to high energies. These charged solar energetic particle (SEP) events were first recorded in 1942 (Forbush, 1946). Because of the low sensitivities of ground based measurements, it was first thought that these events were rather rare. However, increasing use of satellites with their ability to remain outside of the terrestrial magnetic and atmospheric "shield" have shown that SEP events are not rare. They are an almost daily occurrence during solar maximum. In fact, McCracken et al. (1967) have stated that 80% of all solar flares, greater than importance 2B, generated observable SEP events. They even suggest that with increased sensitivity, it will be found that all solar activity may result in the production of SEP's.

The physical processes that control the trapping, acceleration, storage, and release of the solar energetic particles at the sun are still not understood. One of the reasons for this is the strong interaction of the charged SEP's with the interplanetary and solar magnetic fields. It can probably be stated that the study of SEP events has helped more in the
understanding of interplanetary conditions than they have in the understanding of the processes that produced the event itself. One way of overcoming the problem of the magnetic fields is to observe these events by way of the high energy neutral radiation that must be produced at the sun during the acceleration and storage of these particles.

Estimates of neutron and gamma ray production in association with solar flares were first made by Biermann et al. (1951) and Morrison (1958) respectively. Many experimental and theoretical studies have been made since then. References to these, as well as extensive quantitative calculations, have recently been completed by Lingenfelter and Ramaty (1968). (Hereafter referred to as L & R). Using a very general model, L & R predict measurable fluxes of neutrons and gamma rays should be emitted during large solar flare events. They also show that the observation of these will indeed provide information about the SEP event that cannot be obtained from the charged SEP's themselves. If only upper limits on these fluxes can be set, these will provide important constraints on any possible flare event models.

It should also be pointed out that there exists evidence for the continuous emission of charged particles from the sun (McCracken et al., 1967). Hence, some of the process considered by L & R might also be taking place on a smaller scale continuously in time.

The understanding of solar flares is, of course, interesting in its own right. However, our sun has the
further property of being a very ordinary star. Hence, processes and events on the sun are expected to be very much like those on the vast majority of the stars in the universe. In particular, the study of solar flares may have a bearing on the production of galactic cosmic rays. Our sun, through the SEP's it produces, is a supplier of some of the lower energy galactic cosmic rays. Also, if neutrons and gamma rays are being produced in nuclear reactions on all stars such as our sun, this may have important implications on the abundances of at least the lighter elements in the universe.

The primary objective of this experiment then, was to observe or to set new lower limits on the emission of neutrons by the sun, both during quiet and active solar conditions. This objective should be considered a part of the total effort of the group with which the author was associated. This larger effort was to make simultaneous measurements of both solar gamma rays and neutrons.

There was one secondary objective. This was to study the flux of high energy (> 20 MeV) cosmic ray albedo neutrons. This is an energy region in which there have been very few measurements (Haymes, 1965), and which could be an important supplier of protons for the inner radiation zone. This aspect will be treated in Appendix A.

2. Solar Activity and Solar Energetic Particles

The photosphere (or solar surface) is the region of the sun that is most easily observed in visible light. This
is probably the reason that so much experimental work has been done on photospheric effects. In this region, phenomena can be observed, questions can be formulated, and theories can be checked. However, it is very probable that many of the events and features observed on the photosphere are merely indications of the primary phenomena taking place under the photosphere where direct observation is nearly impossible. Two photospheric effects that have received a lot of attention are sunspots and solar flares.

Individual sunspots are observed as dark spots on the photosphere. The relative darkness is due to lower temperatures in the spot as compared to the surrounding photosphere. Although individual sunspots are seen, most occur in groups. Associated with a sunspot group is a general increase in activity such as turbulence and a large increase in the magnetic field strength and complexity. The sunspot group rotates with the photosphere surface and appears to be a fairly permanent phenomena. Individual groups often remain evident for two or more solar periods (i.e., 60 days). The sunspot group retains its identity during this period even though the individual spots in the group change shape and wander relative to each other. There also seems to be a marked preference for sunspot groups to reform in the same photosphere region. Also associated with sunspots are short-term increases in intensity known as solar flares.

It is interesting that solar flares, although a
very energetic event, are difficult to describe or to see (Zirin, 1966; Chap. 13). The most common definition or description of a solar flare is in terms of its optical energy emission. This is a temporary emission within some of the normally dark Fraunhofer lines, usually the $H_\alpha$ line of atomic hydrogen. Flares are also classified in importance in terms of their optical appearance. This classification is based on the flare's area as seen in $H_\alpha$ emission. However, it should be pointed out that it is not clear what the optical importance has to do with the real importance of the total flare event (Zirin, 1966). Hence, care must be taken when using the optical importance classification for individual flares, especially when other than its optical properties are being studied.

In order not to confuse the optical flare with the total process, we shall talk of the solar flare event. It may be that a solar flare event is best described as a temporary increase in activity and energy emission. It is explosive in nature, the time duration of flare phenomena being in the order of $10^2 - 10^3$ seconds. These events are observed by many means other than visual observation. Radio and X-ray emission are also commonly associated with solar flare events. In fact, DeJager (1967) points out that one should distinguish clearly between the "optical flare" and the "high energy flare" (radio or X-ray flare). The above author (as well as most others) suggests that the radio emission and X-rays are produced by energetic electrons.
These non-thermal electrons, with energies up to ~500 keV, interact with the solar atmosphere and/or magnetic field to produce synchrotron or bremsstrahlung radiation. As mentioned earlier, streams of every energetic charged particle are also associated with flare events. These particles can have energies that exceed 1 Bev, although they are normally of much lower energy. Hence, it may be that one should also define the "extra high energy" or "particle flare".

It may be that solar flares should be thought of in the following way. The originator of the event is most likely an instability. This instability allows the prompt release of the large amounts of energy that have been observed (up to \(10^{32}\) ergs, DeJager, 1967). The source of this energy is thought to arise from the annihilation of the strong magnetic fields that are associated with sunspots (see for example, Wentzel, 1964). At any rate, apparently this energy can be distributed in various ways amongst the optical flare, the radio X-ray flare, and the particle flare. It may be that one or more of the modes are excluded in any given flare. It is not clear how or if these modes are connected, or even if they can be thought of as different modes at all. In fact, it is theoretically difficult to explain how the large amounts of energy involved can be released in such a short time (Wentzel, 1964). Of the three modes, probably the one least understood is the particle flare. It is this property of solar flare events, which controls the acceleration, release, and possible trapping of solar energetic par-
ticles, that is of direct concern in this experiment.

Solar energetic particles (SEP's) have been observed for some time, and their properties, as seen near 1 A.U., are well reviewed (see for example, Webber, 1964; Fichtel and McDonald, 1967; or McCracken et al., 1967). There are some characteristics that are common to most of these SEP events. One of these is their rather steep energy spectrum. Two of the more common representations of the spectrums are, a power law in particle energy, or an exponential law in particle rigidity. In the case of the power law the differential particle flux \( \frac{dJ}{dE} \) is given by:

\[
\frac{dJ}{dE} = C(t) E^{-n(t)}
\]

Here, \( E \) is the particle kinetic energy and \( n(t) \) is the time dependent power index. This index usually lies between 3 and 6. For the exponential law the differential flux \( \frac{dJ}{dP} \) is given by:

\[
\frac{dJ}{dP} = \frac{dJ_0}{dP} \exp \left[ -\frac{P}{P_0} \right]
\]

Here, \( P \) is the particle rigidity and \( P_0 \) is a characteristic rigidity, again usually time dependent. The particle rigidity is given by:

\[
P = A/Z_e \left[ E^2 + 2E M c^2 \right]^{1/2}
\]

where \( A \) is the atomic number, \( Z_e \) is the total charge, \( M c^2 \) is the single nucleon's rest energy, and \( E \) is the kinetic energy.
energy per nucleon.

The elemental abundances of the SEP's are characteristic of those expected at the solar photosphere or lower corona, while the optical flare appears to occur much higher above the solar surface. However, there may be some preferred acceleration which could account for this.

Studies of the time behavior of the SEP events have also been revealing. This is especially true of the more energetic particles. These studies indicate that the release, if not the acceleration, of the SEP's is closely connected with the flash phase or beginning of the optical flare. This is also the time of occurrence of certain types of radio and X-ray bursts often associated with SEP events. This time correlation is based on the assumption that the charged particles travel along a "garden-hose" interplanetary field. The term "anisotropic diffusion" is often used to describe the particles' motion along these field lines.

In spite of the above similarities the single most noticeable feature of all SEP events is the large variations in all of the particle parameters. Certainly some of this variety is induced on the particles after they have left the sun. For example, many of the event parameters are a strong function of the position of the associated optical flare's position on the solar disk, as well as the conditions that exist in the interplanetary field. To study the conditions on the sun it would be helpful if all of these induced variations and effects could be removed. In other words, it is
most important to know the parameters of the SEP's during or immediately after their acceleration, possible trapping, and release.

Some of the more interesting parameters that should be determined are the time dependence of the acceleration, the position and size of the acceleration region, the flux intensity, and spectrum shape as well as the time of particle release. Some of this information has been laboriously unfolded from the observation of the SEP's at 1 A.U. These include the above mentioned time of release that is correlated with the optical flash phase. The time interval during which particle release occurs appears to be less than $10^3$ seconds. There are also estimates of the total number of particles released. However, some of the other parameters are much more difficult, if not impossible, to determine from observation of the charged SEP's alone.

What is needed is a probe that is not affected by the solar and interplanetary fields. This probe must also allow investigation of the above interesting parameters. Fortunately, there does seem to be such a probe. This would be the neutral secondaries produced by the SEP's at the sun while being accelerated, trapped, and/or released.

SEP's, while at the sun, must interact with the residual solar atmosphere. These interactions will result in the production of both charged and neutral secondaries. The neutrals, which include both neutrons and gamma rays, are not appreciably affected by either the solar or interplanetary
magnetic fields. The high energy of the SEP's combined with any reasonably sized acceleration volume and time interval indicate that the emission of these neutrals will be approximately isotropic in space. Neutral secondaries which result from the trapping and stopping of the SEP's in the photosphere will also be emitted isotropically (Lingenfelter et al., 1965). Some of the expected properties of these neutral secondaries will now be discussed. These will be based on estimated, but hopefully reasonable, properties of both the acceleration region and the SEP's at the sun. These estimations are inferred from optical observations, as well as observations of SEP's at 1 A.U. Hence, if the predicted secondary production proves to be true, it would imply that we had correctly interpreted the earlier measurements. However, if the predicted secondaries are not seen, then the earlier observations and interpretations must be re-evaluated.

3. Solar Neutrons and Gamma Rays

Most of this section will be composed of a review and discussion of the results obtained by Lingenfelter and Ramaty, (1967) (i.e. L & R). Their results are the most comprehensive of any published thus far. The model used by L & R was first suggested by Hess (1962). It assumes that the SEP's are accelerated in a region of the solar atmosphere above the photosphere. Some of these particles then escape from the sun and are seen near the earth. Others, however, could be directed downward to be stopped in the
photosphere. These latter particles would be very efficient producers of neutral secondaries which could themselves escape from the sun. They would provide information about the SEP's immediately after their escape from the acceleration region.

In order to make quantitative predictions, certain other assumptions were also necessary. One of these was that the SEP's energy spectrum at the sun is similar to that measured near the earth. In this case it was taken to be exponential in rigidity with a characteristic rigidity $P_0$. Another assumption was that the elemental abundances in the acceleration and trapping regions are the same as those in the solar atmosphere.

The best known solar abundances and nuclear cross-sections were used to determine what types of secondaries could be produced. The intensity and, where applicable, the energy spectra and time dependence of the interesting secondaries were then calculated. The calculations give the yield of these secondaries for different charged particle spectral shapes. They are given as a function of the amount of material traversed by the SEP's while being accelerated and escaping; and also as a function of the number of SEP's that are trapped in the solar atmosphere. The yields were normalized to one proton greater than 30 MeV.

Estimates of the amount of material traversed by the SEP's in the acceleration region were made by comparison of the calculated and measured $^1\text{D}^2$, $^1\text{T}^3$, and $^2\text{He}^3$ isotope to
proton ratios. These (see discussion of measurements in L & R) indicate depths in the order of 1-5 g/cm$^2$. These depths were then used to determine the yields of the other secondaries for specific flares.

The most intense neutral secondaries were found to be (i) high energy neutrons, (ii) 0.51 MeV gamma line from positron annihilation, (iii) 2.2 MeV gamma line from neutron capture in hydrogen, (iv) 4.4 and 6.1 MeV gamma lines from nuclear de-excitation of $^{12}$C* and $^{16}$O*, and (v) the high energy (> 10 MeV) gamma ray continuum from neutral pion decay. The relative intensity of the above radiations was found to be dependent on the characteristic rigidity of the accelerated SEP's. High energy neutrons and the 0.51 and 2.2 MeV gamma ray lines are the most intense, especially for low characteristic rigidities ($P_0 \leq 100$ MV). These three radiations, however, can have the disadvantage of being spread out in time at 1 A.U. The neutron's time of arrival at 1 A.U. is, of course, dependent on its energy. The rate of production of the 2.2 MeV and the 0.51 MeV gamma lines at the sun can be governed by the neutron and positron emitters lifetime against decay. These lifetimes are both in the order of $10^3$ seconds. However, the 4.4 and 6.1 MeV gamma ray lines and the high energy gamma ray continuum are very prompt. In fact, the intensity of these prompt gamma rays at 1 A.U. is directly proportional to the product of the time dependent SEP distributions and the ambient densities in the flare region.
It is interesting to note that, if the SEP's acceleration and trapping times on the sun are, as L & R assume, in the order of $10^2 - 10^3$ seconds, then neutrons and the lower energy gamma ray lines would be easier to detect. These measurements would, however, provide less information on the time histories of the acceleration and trapping phenomena. On the other hand, if the acceleration and trapping times are much shorter (1 - 10 seconds), then the higher energy gamma rays could be easier to detect because their instantaneous rates would be higher.

Finally, it should be pointed out that, to the author's knowledge, there is not yet any unambiguous evidence for the occurrence of energetic solar neutral radiation. However, as L & R point out, this lack of evidence does not contradict their calculations. What is needed are measurements with more sensitive detectors during the times when active solar flare events are occurring. The rest of this thesis discusses the results of such an effort.*

*Some of the results to be discussed will be published in Forrest, D. J. and E. L. Chupp, Upper limit for the solar neutron flux in the energy interval 20-120 MeV, Solar Physics, 1969.
SECTION II

EXPERIMENTAL DETAILS

1. Design Limitations

Lingenfelter and Ramaty (1968) have calculated the secondary solar neutron spectrum and intensity at the sun. They then followed the flux to 1 A.U. In order to allow the reader to better understand the experimental design requirements, some of their pertinent results will be restated here. The first important result is that the solar neutron energy spectrum at 1 A.U. has a broad maximum between 15 MeV and 60 MeV. This maximum is due to the low survival probability of low-energy neutrons and the steep energy spectrum of the charged SEP's. The second result is that for neutrons emitted impulsively from the sun, the sun-earth distance acts as a line of flight spectrometer. High energy neutrons arrive ~700 seconds after being emitted from the sun. Lower energy neutrons will arrive at predictable later times. The total duration of a solar neutron event at 1 A.U. is ~10³ seconds. This is the shortest possible duration and would not appreciably change if the neutrons are emitted by the sun in a time interval as long as 10² - 10³ seconds. If the emission interval exceeds ~10³ seconds, the neutrons will no longer be monoenergetic in time at 1 A.U. Also the event duration at 1 A.U. will become longer, and the
peak flux will be lower.

The above information suggests a number of desirable detector properties. First the detector should have good sensitivity for high energy neutrons and low sensitivity for neutrons below ~10 MeV. This will reduce the background produced by the steep atmospheric neutron spectrum. Second, since impulsively emitted neutrons can be monoenergetic in time, a detector with only crude energy resolution may be sufficient. Finally, the detector should have a time response that is less than $10^2$ seconds. Detection schemes that require much longer observation times to improve statistics will not suffice.

Any balloon borne experiment must satisfy certain weight, power and reliability restrictions. In a search for solar neutrons these restrictions become more acute. Importance 1 or smaller solar flares are nearly a daily occurrence during solar maximum. Larger solar flares which statistically tend to produce more interesting SEP events, are more rare. These large flares tend to be grouped together in time when there is an active and growing sunspot group present on the sun. The average probability of importance 3 or greater flares is in the order of one per 20 to 30 days during solar maximum. A single balloon borne experiment, on the other hand, can expect a maximum of 10 to 18 hours of flight every 4 to 7 days. Hence, it is advisable to pick a flight day when the large flare probability is higher than average.

The Environmental Science Service Administration
(ESSA) at Boulder, Colorado, issues a Space Disturbance Forecast Bulletin. These bulletins, using solar data collected from many stations, give the probability of various size flares for the proceeding three days, and can be used to pick a good flight day. However, in order to use these forecast bulletins, the experimental equipment must be reliable so that it can remain on stand-by for up to 30 or more days, and then be prepared for flight on a few hours notice. The equipment should also be as light in weight as possible. This allows use of smaller balloons that can be launched in more marginal surface winds. Another requirement is very long flights. The probability of observing a flare on any given flight is proportional to the flight duration. At the balloon launching station in Texas, the high altitude winds during ~ 80% of the year are such that the balloon is out of telemetry range in < 6-8 hours. To obtain longer flights, either down wind telemetry stations are needed or the data must be recorded on the balloon package. On-board recording is by far the easiest, both logistically and for check out purposes. Balloon package recovery probabilities of 95-98% give no reliability handicap to this method. The last problem is the design of the particular detector to be used. The requirements discussed above must be kept in mind while doing this.

There are two general types of detectors that can be used in a search for solar neutrons. The first is a directional detector which can uniquely define the source
by pointing the detector toward and away from the sun. The second is a non-directional detector with high efficiency. With this latter type, the high altitude neutral radiation intensity would be monitored and variations associated with the sun searched for. A diurnal effect would be expected if the sun emits neutrons continuously. Transient changes during the solar day would be expected if the sun emits neutrons impulsively.

Directional neutron detectors normally use the $^1\text{H}(n,p)n^-$ reaction. The cross section for this reaction is well known and because it is a two body interaction, its kinematics can be calculated exactly. Directional solar neutron detectors using this reaction have been proposed by Pinkau (1966) and White (1968); and one has been constructed and flown by Zych (1968). Briefly, Pinkau (1966) proposed a detection scheme in which the neutron would be scattered twice, once in each of two spark chambers. The angle and energy of the two scattered protons then allow a unique determination of the incident neutron's direction and energy. White (1968), on the other hand, would allow the neutron to double scatter in two hydro-carbon scintillators. The first scattered proton's energy would be determined by its light output, while the scattered neutron's energy would be determined by its time of flight to the second detector. This method does not determine a unique incident neutron direction, however. Zych's (1968) detector was also a spark chamber, in which the recoil protons could be observed.
This detector and the results of its flight will be discussed more fully in Section IV. Another somewhat simpler directional detector has been flown by Sydor (1965). This was a thick target recoil-proton detector. While its directionality is only fair (FWHM = 30°) and its efficiency is low, the efficiency does increase with increasing neutron energy. These detectors, while providing directionality, must work with a small cross section that is decreasing with increasing neutron energy. Because of the low efficiencies, the area of these detectors must be made very large (i.e., square meters). This results in very elaborate, heavy, and complicated equipment.

Non-directional neutron detectors are normally very simple compared to the above directional detectors. Only two types of non-directional detectors were found to have sufficient sensitivity to warrant consideration. The first was the moderated BF$_3$ or He$_3$ detector (Hess and Kaifer, 1967; Bame and Asbridge, 1966). In this type of detector, high energy neutrons are slowed down or moderated by a high hydrogen content moderator. The low energy neutrons are then detected in an He$_3$ or BF$_3$ proportional counter. The response to high energy neutrons can be increased by making the moderator large. This detector provides no spectral information and has high efficiency for low energy neutrons. The second type considered was the large plastic scintillator. For neutrons below 10-15 MeV, the most important reaction in hydrocarbon plastic scintillators is elastic scattering
from hydrogen (i.e., $^1H(n,p)n'$). In this energy range pulse shape discrimination can be used to remove gamma ray effects, and spectrum unfolding can be used to determine the original neutron spectrum (for example, see Haymes, 1964). However, for neutrons above ~15 MeV, reactions involving carbon quickly predominate over those in hydrogen. Although the details of the $^{12}C(n$, charged particle) reactions are not well known, the total detection efficiencies of large plastic scintillators for high energy neutrons has been experimentally determined (Wiegand et al., 1962; Crabb et al., 1967; Brady et al., 1968). These studies show that the sensitive energy region can be controlled by appropriately placed bias levels and that the efficiency remains reasonably high and constant for neutrons above 150 MeV.

Before discussing the final experimental design, let us consider some of the statistical limitations that apply to the measurements of these small fluxes. All conceivable solar neutron detectors will be "background limited". That is, to be recognized, the counting rate produced by the small signal flux must exceed the statistical variations of a larger, but known, background rate. The smallest flux that can be seen in this case can be calculated (See Parratt, 1961, Sec. 5-8; or Evans, 1955, Chap. 26). Let $R_{s+b}$ and $R_b$ be the counting rates of the signal plus background and the background alone. Then, the signal rate is given by:

$$R_s = R_{s+b} - R_b \pm \left(\frac{R_{s+b}}{T_{s+b}} + \frac{R_b}{T_b}\right)^{1/2}$$

II-1
If \( R_s < < R_b \), it can be shown that the error in the above measurement for a total counting time \( 2T \) is a minimum when \( T_{s+b} = T_b = T \). Given this, \( R_s \) has a greater than 98% probability of being real if:

\[
R_s > 3 \left( \frac{2R_b}{T} \right)^{1/2}
\]

This expression assumes only that the statistical variations predominate over all others, and that these variations follow the normal frequency distribution (i.e., \( R_b T > 1 \)). If \( R_b T = 1 \), the Poisson frequency distribution must be used and the minimum \( R_s \) is somewhat larger than the limit given above. If a Chi-square test indicates that the variations in the counting rates \( R_b \) and \( R_{s+b} \) are not strictly due to counting statistics, then a computed standard deviation (\( \sigma_{com} \)) must be used in Eq. II-1. Eq. II-2 would then become:

\[
R_s > 3 \left[ \sigma_{com}^2 (s+b) + \sigma_{com}^2 (b) \right]^{1/2}
\]

To convert these counting rate limits into a flux, we note that approximately, \( R_s = F_s S \); where \( F_s \) is the signal flux with units of \( \text{area time}^{-1} \) and \( S \) is the sensitivity of the detector for the flux \( F_s \). The sensitivity is defined as the detector response, in counts per unit time, to a unit incident flux. It is normally the product of the detector's efficiency times its area. Hence, the minimum flux that can be seen \( (F_{s \text{ min}}) \) is given by:

\[
F_{s \text{ min}} > \frac{3}{S} \left( \frac{2R_b}{T} \right)^{1/2}
\]
This expression makes clear the advantages of the directional detector. An ideal directional detector, because it will only accept events from a small solid angle, can reduce $R_b$ by large factors without, in theory, reducing $S$.

Eq. II-3 was used to compare the various detectors. The limits that could be set with reasonable size directional detectors appeared to be only marginally better than those with non-directional detectors. Even this improvement was dependent on estimates of the background counting rates. It is very difficult to estimate this, in view of the mixed radiation environment at balloon altitudes. Earlier experiences with a directional neutron detector (see Appendix B; or Forrest, 1967) showed this difficulty. Directional detectors were finally ruled out because of their complexity and weight, poorer time response, and only marginally improved performances.

The final detector choice was a large plastic scintillator. This was dictated by its high neutron sensitivity, simple and light weight construction, and the ease with which onboard recording could be accomplished. Pulse shape discrimination against gamma rays was not attempted because it was thought that the background from gamma rays would be approximately the same as that from atmospheric neutrons (Haymes, 1964) which could not be discriminated against. In order to monitor the gamma ray flux a second detector was included. This was a $5.1 \text{ cm} \times 5.1 \text{ cm}$ CsI(Na) scintillator. The general gondola design and the properties of these two
detectors will be discussed next.

2. Description of Experimental Apparatus

The experimental equipment consisted of the two detectors and their associated electronics, recording system, balloon gondola and other housekeeping equipment. The neutron detector was a large cylindrical NE 102 plastic scintillator, which was viewed by three photomultiplier tubes. These components were completely surrounded by a 1.9 cm thick plastic scintillator charged particle shield. The output pulse height distribution of the neutron detector was crudely determined by three integral discrimination levels. The equivalent energy loss for protons, alphas, and electrons corresponding to the three bias levels are given in Table II-1. The second detector was a CsI(Na) scintillator also completely surrounded by its own plastic scintillator charged particle shield. It too was equipped with three integral level discriminators with energy thresholds as shown in Table II-1.

The operation of the two detectors, except for common low voltage power supplies and the recording system, was completely independent. Each detector, along with its complete charged particle shield, electronics circuitry, and high voltage DC-DC converter, was in its own pressurized and thermostatically controlled container. The rates from the three integral level discriminators and the charged particle shield of each detector were electronically scaled and recorded on photographic film. A clock pulse and the tempera-
<table>
<thead>
<tr>
<th></th>
<th>NE 102 Plastic Scintillator</th>
<th>Csl(Na) Scintillator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
<td>12.7 cm diameter 5.1 cm length</td>
<td>5.1 cm diameter 5.1 cm length</td>
</tr>
<tr>
<td><strong>Bias levels (MeV)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>proton energy equivalent ($B_p$)</td>
<td>7±1, 15±2, 21±3 MeV</td>
<td>---</td>
</tr>
<tr>
<td>alpha energy equivalent ($B_a$)</td>
<td>26±3, 43±6, 55±9 MeV</td>
<td>---</td>
</tr>
<tr>
<td>electron energy equiv. ($B_e$)</td>
<td>3.0±0.5, 9±1, 13.0±1.5 MeV</td>
<td></td>
</tr>
<tr>
<td>scaling factors</td>
<td>5x10^2, 2x10^2, 10^2</td>
<td>10^2, 50, 20</td>
</tr>
</tbody>
</table>

**Approximate Neutron Sensitivity**

- bias level #1: $36 \text{ cm}^2$ ($20<E_n<120 \text{ MeV}$) < $0.6 \text{ cm}^2$ ($E_n<100 \text{ MeV}$)
- bias level #2: $25 \text{ cm}^2$ ($50<E_n<120 \text{ MeV}$) < $25 \text{ cm}^2$ ($25<\gamma<50 \text{ MeV}$)
- bias level #3: $20 \text{ cm}^2$ ($70<E_n<120 \text{ MeV}$) < $6 \text{ cm}^2$ ($35<\gamma<50 \text{ MeV}$)

**Approximate Gamma Sensitivity**

- bias level #1: $38 \text{ cm}^2$ ($3<\gamma<20 \text{ MeV}$) < $8 \text{ cm}^2$ ($10<\gamma<50 \text{ MeV}$)
- bias level #2: $7 \text{ cm}^2$ ($25<\gamma<50 \text{ MeV}$)
- bias level #3: $6 \text{ cm}^2$ ($35<\gamma<50 \text{ MeV}$)

**C.P.S. Scaling Factor**

- NE 102 Plastic Scintillator: $10^4$
- Csl(Na) Scintillator: $5\times10^3$
ture in each pressure container were also recorded during the flight.

The electronics for each detector were basically the same. Figure II-1 shows a generalized block diagram for either detector. The photomultiplier's anode pulse was temperature compensated, delayed and clipped in a pre-amplifier (T.C. Preamp & Delay). This circuit (Figure II-2) was mounted inside the charged particle shield and near the photomultiplier-scintillator combination that was to be temperature compensated. The output from the preamplifier then goes to the three tunnel diode discriminators (DISC #1,2,3). These discriminators (Figure II-3) are inherently temperature stable in that the peak current temperature stability of the IN2939 tunnel diode is ≈0.5% from -20°C to +60°C. The discriminator outputs are then standardized by a one-shot monostable (Mono) and placed in anticoincidence (A.C.) with the output of the charged particle shield. Outputs that are not in coincidence with a charged particle shield event then go on to the scaling circuits. The delayed linear output (Delayed Linear Out) was used for testing and setting of the discriminators only.

The outputs from the charged particle shield photomultiplier first go through a preamp (CPS Pre Amp) to a discriminator and one-shot monostable (CPS Disc & Mono). The output of this monostable then goes to the anticoincidence circuits and to the scaling circuits. Because of the awkward geometry of the charged particle shields the light
Figure II-1. A generalized block diagram which pertains to either the Csl or the plastic detector.
Figure 11-2

$T_1 = 2N3638$

$T_2 = 2N3646$

$R_2$ is a sensor-resistor combination to temperature compensate.

$R_1$ is set to clip pulse at $\approx 5V$

$R_L$ is anode load resistor, pick for $\approx 2\mu s$ pulse decay.

Temperature compensating preamp and delay
Tunnel diode discriminator

Figure 11-3

200 1-5 K IN2939 2N1308

10 K +9 V

One shot monostable

2 μs
collection efficiency is very poor. A \( \mu \)-meson telescope was used to find the position on the shield where the output pulse from a minimum ionizing through particle is smallest. The discriminator was then set to trigger on a pulse approximately \( \frac{1}{3} \) the size of this smallest possible pulse. This discrimination triggering level was always well above the photomultiplier noise. The charged particle shield discriminator was essentially the same as that shown in Figure II-3.

The various outputs were electronically scaled down to rates that could be handled by the camera recording system. The scaling elements were micrologic decade counters. The total scaling factor in each output was calculated to give one scaled output pulse on the film every 10 to 20 seconds. This, then, is the time response of the detection scheme. The scaling factors used are given in Table II-1.

The recording camera was designed and built for this experiment. It consisted of a light tight box in which 35 mm film was driven past a recording head at a constant velocity of \( \approx 1.5 \) mm/sec. The recording head was drilled with 16 holes spaced across the ~30 mm width of usable film. These holes were in turn connected by flexible light guides to 16 miniature light bulbs. The light bulbs were pulsed on by the scaling circuits, the clock or any of the other housekeeping circuits. After the film is developed, the number of pulses in each channel per unit length of film is read off by hand. From the known period of the clock, the rate
of pulses per unit time in the other channels can be calculated.

The clock pulses were generated from an ordinary wind-up type alarm clock. The face of the clock was replaced with a printed circuit board. This board was figured so that a sliding contact on the minute hand completed a closed circuit to a camera light bulb every 300 seconds. Two closures in succession were made on the hour. Hence, by recording the approximate time at which the camera film started to advance, the absolute time as well as time intervals were recorded. On the last flight a crystal-controlled oscillator was used in addition to the clock to supply a very accurate timing pulse. The results of this flight showed that the clock's timing errors did not significantly contribute to the overall experimental errors.

The temperature in the CsI detector's pressure shield was measured by a thermistor controlled astable oscillator, which directly fired a light in the camera. The temperature in the larger plastic detector's pressure shield was recorded on a clock driven recording thermometer. The thermostatically controlled heaters were set to go on when the temperature in the pressure containers fell below \(-17^\circ C\).

The high voltage needed for the photomultipliers was supplied by commercial DC-DC converters. These units can supply regulated 1000 volts at 3 ma from an unregulated voltage supply of \(28 \pm 3\) volts. One of these converters was used for all the photomultipliers in each pres-
sure shield.

A schematic drawing of the detector system is shown in Figure II-4. The batteries, camera, and other equipment common to both detectors was placed in the large spherical pressure container. This material was kept as near the bottom of the container as possible. The total weight of the gondola, including an aluminum frame, was $\approx 200$ pounds. This represents an average thickness of material between the basic neutron or gamma ray detectors and the atmosphere of $4$ to $5 \, \text{g/cm}^2$. Most of this material was low Z and consisted of the plastic charged particle shield, fiberglass pressure containers, and polystyrene thermal insulation.

The system was completed in June 1967 and has since completed four balloon flights. It has proven to be reliable, easy to maintain, and immune to noise pickup. The measured thermal coefficient of the detector's counting rates was less than $0.3\%/^\circ\text{C}$. This coefficient plus the good temperature stability ($\pm 7^\circ\text{C}$) of the gondola during a balloon flight and the fact that the detector's temperature excursions would be less than that of the gondola made corrections due to temperature changes neglectable. A series of ground level background runs made before and after each flight have shown no significant changes.

The response of the two detectors to neutrons and gamma rays will be discussed in the next two sections.
Figure II-4. A schematic drawing of the complete detector system.
3. Plastic Detector Response

The neutron detection efficiency of large plastic scintillators has been experimentally determined for a wide variety of bias levels and detector sizes. Wiegand et al. (1962) have determined the efficiencies of a plastic detector 15 cm thick and with a bias level of ≈ 4 MeV proton energy equivalent for neutron energies, 4 MeV < E_n < 76 MeV. Crabb et al. (1967) used a 28.6 cm thick scintillator with a bias level of ≈ 6 MeV. The neutron energy range they covered was 20 < E_n < 130 MeV. Brady et al. (1968) used a detector 30.5 cm long with bias levels of 3.5, 5.2, 8.3, and 24.5 MeV. Their energy range was 20 < E_n < 170 MeV. Finally, Bowen et al. (1962) determined the efficiencies of a 2 cm thick liquid scintillator at a bias level of 1.7 MeV for 15 < E_n < 120 MeV. This information constitutes an experimental verification of the neutron detection efficiency for the present detector.

However, in order to use all of the above data and to calculate the off axis efficiencies, a semi-emperical equation for the efficiency was derived. The equation used was qualitatively correct, but included one undetermined parameter. This parameter was varied for a best fit to the above experimental data.

The flux J(E_n) of unscattered neutrons of energy E_n at a distance (l) from a detector's front face is given by J(E_n) = J_0 exp (-\lambda l). Here, J_0 has the dimensions of neutrons/cm^2 sec and \lambda is the inverse of the neutron's absorp-
tion mean free path in the detector and has the dimensions of cm$^{-1}$. If the detector is a plastic scintillator the number of neutrons that will interact in the element $dl$ at $l$ and be detected is just:

$$dJ = J_0 \left( n_H \sigma_H + n_C \sigma_C \right) \exp(-\lambda l) dl$$

where:

- $n_H$ and $n_C$ are the number densities (cm$^{-3}$) of hydrogen and carbon atoms in the scintillator.
- $\sigma_H$ is the total neutron cross section (cm$^2$) in hydrogen.
- $\sigma_C$ is the neutron cross section (cm$^2$) for producing charged particles in carbon.
- $f_H$ and $f_C$ are the fraction of these interactions that release sufficient energy to exceed the bias level and hence are detectable.

The factor $\lambda$ equals $(n_H \sigma_H + n_C \sigma_C)$, where $\sigma_C$ is the inelastic neutron cross section in carbon. The elastic scattering portion of the total carbon cross section is not effective in changing either the neutron's energy or direction because of the relative large mass of carbon (Nakada et al., 1958).

At low energies the n-$H^1$ differential scattering cross section is isotropic in the center of mass system. From this it can be shown that the fraction of recoil protons above a given bias level $B_P$ is, $f_H = 1 - B_P/E_n$. At higher energies the scattering cross section is not quite
isotropic; however, the above approximation introduces errors of only a few percent if $B_p/E_n < 1$ (Rybakov and Sidorov, 1960). Hence, to a good approximation, we get after integrating from 0 to $L$:

$$
\varepsilon(E_n) = J/J_o = \frac{n_H\sigma_H(1-B_p/E_n) + n_c\sigma_c f_c}{n_H\sigma_H + n_c\sigma_c} \left[ 1 - \exp\left(-\left(n_H\sigma_H + n_c\sigma_c\right)L\right) \right]
$$

Bowen et al. (1962) have determined the cross section for $^{12}$C (n, charged particles), for charged particles with energies greater than 1.7 MeV proton energy equivalent. Their values are called $\sigma_c'$ here and are equal to the $^{12}$C inelastic cross section for neutron energies above 25 MeV and were used for both $\sigma_c'$ and $\sigma_c''$.

To fit the above equation to the experimental efficiencies it was assumed that, at least for neutron energies near the bias energy, the most important reactions in carbon were $^{12}$C(n,n')3α or $^{12}$C(n,α)Be9. The term $f_c$ was then assumed to be of the form $[1 - (B_\alpha/E_n)^m]$ and $m$ was varied for a best fit to the data. Note that $B_\alpha$ is the bias level in alpha energy equivalent and must include the negative Q of the above reactions as well as the non-linear scintillation efficiency of alpha particles in plastic scintillators (Gooding and Pugh, 1960). It was found that $m = 1.5$ gave the best fit to all the experimental data, although the efficiency was not strongly dependent on $m$.

Figure II-5 shows the values of $\sigma_H$ and $\sigma_c'$ used in
Figure II-5. The cross sections $\sigma_\text{H}$ and $\sigma_\text{C}'$ used with Equation II-4 to calculate the neutron detection efficiencies of the plastic detector. The solid line is a smooth curve drawn to fit Bowen et al. (1962) experimental points.
these calculations. Figures II-6 show the experimentally determined efficiencies and the results of the final efficiency equation:

\[ \varepsilon(E_n) = \frac{n_H \sigma_H (1-B_p/E_n) + n_c \sigma_c (1-(B_\alpha/E_n)^{3/2})}{n_H \sigma_H + n_c \sigma_c} \cdot \left[1-\exp\{-n_H \sigma_H + n_c \sigma_c \}L\right] \]  

II-4

when the appropriate values of \( B_p, B_\alpha, \) and \( L \) are used. For example, in Figure II-6, Crabb et al. (1967) used a detector with \( L = 28.6 \) cm, and \( B_p = 6 \) MeV proton energy equivalent. The threshold for either of the \( ^{12}C(n,\alpha...) \) reactions is \(- 8 \) MeV and it requires a 16 MeV alpha particle energy loss to equal the light output from a 6 MeV proton energy loss. This implies \( B_\alpha = 24 \) MeV.

Equation II-4 was used to determine the efficiencies for the bias levels used in the present experiment. These were 7 MeV, 15 MeV, and 21 MeV proton energy equivalent. The bias levels were experimentally determined on the actual detector by the same method used in all three of the above experimental papers. This consists of calibrating the detector with the known energy Compton edges produced in the scintillator by monoenergetic gamma rays. The electron energy calibration is then converted to proton energy with the known relative light output for protons and electrons.
Figure II-6. A comparison of experimentally determined neutron detection efficiencies with those calculated from Equation II-4.
Finally, the sensitivity of the plastic neutron scintillator was computed. Because the mean free path for high energy neutron is large (i.e., $\lambda L \ll 1$) the sensitivity of the detector is isotropic within the estimated ± 15% errors of the efficiency calculation. The sensitivity of the present detector as a function of neutron energy is shown in Figure II-7.

It should be pointed out that neither the experimental or the calculated efficiency considers the effect of the active $4\pi$ charged particle shield. The presence of this shield could affect the efficiency in two ways. First, a neutron scattered in the central detector could be rescattered in the shield to produce a veto pulse. A veto pulse could also be produced if an energetic charged particle, produced by a neutron, leaves the central detector and enters the charged particle shield. To estimate the first case we note that all neutrons which escape from the central neutron detector must pass through the charged particle shield. Bowen et al. (1962) have determined the efficiency of a 1.9 cm thick liquid scintillator for a bias level of 1.7 MeV proton energy. The efficiency is $\approx 7\%$ for a 10 MeV neutron and $\approx 3\%$ for neutrons greater than 50 MeV. Hence the present charged particle shield with a thickness of 1.9 cm and a bias level of $\approx 3$ MeV proton energy will detect less than 7% of the neutrons which escape from the central detector. This correction was neglected.
The calculated neutron sensitivities of the three discrimination levels of the present plastic detector.
The evaluation of the self-gating effect due to energetic recoil protons is more difficult because of the lack of information on the n-c$^{12}$ reactions. There is information at one neutron energy, however. Kellogg (1953) found for 90 MeV neutrons on carbon a total star formation cross section of 232 ± 17 mb. The cross section for producing protons ≥ 20 MeV was 85 ± 10 mb. At the same energy, Hadley and York (1950) found a proton producing cross section of 90 ± 20 mb in carbon. They also found that ≥ 80% of the energetic protons were emitted between 0°-45°, with an energy spectrum that was constant between $E_p = 0$ and $E_p = E_n - 15$ MeV. Hence, including the H$^1$(n,p)n$^\prime$ cross section of ≥ 90 mb, approximately 1/2 of the total calculated efficiency at $E_n = 90$ MeV results in the production of energetic protons that could contribute to self-gating.

To estimate the self-gating from this effect we note that both the H (n,p)n$^\prime$ and C$^{12}$(n,p...) reactions emit their protons with approximately the same flat energy spectrum. Hence the probability of a proton that is produced by a neutron of energy $E_n$ being in the energy interval $E_p$ to $E_p + dE_p$ is independent of $E_p$ and is equal to $E_n^{-1}$. We make the further simplifying, but nearly correct, assumption that the original neutron is equally likely to interact anywhere in the detector. Then the probability of this proton with energy $E_p$ of producing a self-gating event (i.e., escaping from the detector) is just $R(E_p)/L$. Here $R(E_p)$ is the range of the proton in the detector, which is of length L. Hence
the portion of the total efficiency ($\Delta \varepsilon$) that results in self-gating at a neutron energy $E_n$ is:

$$\Delta \varepsilon = \int_0^{E_n} \frac{\varepsilon/2}{E_n} \frac{R(E_p)}{L} \, dE_p$$

Now the range of protons, in the energy interval of interest, is: $R(E_p) = R_0 E_p^{1.8}$ (Evans, 1955, Chap. 22). Therefore, the fractional efficiency loss due to self-gating will be:

$$\frac{\Delta \varepsilon}{\varepsilon} = \int_0^{E_n} \frac{R_0}{2E_n L} \frac{1.8}{E_p} \, dE_p = \frac{R(E_n)}{5.6L}$$

The minimum detector dimension is $= 12$ cm and the range in NE 102 of a 120 MeV proton is 10 cm. Therefore, the loss of efficiency due to self-gating at $E_n = 120$ MeV is $\leq 15\%$. At 200 MeV this equation predicts $> 60\%$ of the calculated efficiency remains after correction for self-gating. Because 120 MeV was the maximum neutron energy considered, this correction was not made.

A plastic scintillator is not only a good neutron detector but it also has high efficiency for gamma rays. Although the gamma ray efficiency is not needed for the solar neutron measurements it is determined here so that the atmospheric gamma ray and neutron components can be separated.

Gamma rays in the energy region 3-30 MeV interact in plastic scintillators mainly through Compton scattering
(Keszthelyi et al., 1961). However, in plastic scintillators, high energy electrons (< 100 MeV) lose their energy mainly by ionization and have very long ranges. This will reduce the efficiency for high energy gamma rays because of self-gating in the charged particle shield.

Consider a flux \( J_0 (\text{cm}^{-2}\text{sec}^{-1}) \) of gamma rays of energy \( E_{\gamma} \) incident on the face of a plastic scintillator. At a depth \( l \) (cm\(^{-1}\)) the flux \( J \) of remaining original gamma rays is:

\[
J = J_0 \exp(-\lambda l)
\]

Here \( \lambda \) is the total inverse absorption mean free path. The number \( (dJ) \) of gamma ray producing an energy loss greater than the bias level \( (B_e) \) in the interval \( dl \) at \( l \) is:

\[
J = J_0 n_e \left[ \sigma_{\text{CO}}(> B_e) + \sigma_p \right] \exp(-\lambda l)dl
\]

where:

- \( n_e \) is the electron density (cm\(^{-3}\))
- \( \sigma_{\text{CO}}(> B_e) \) is the Compton cross section per electron (cm\(^2\)) for a gamma ray of energy \( E_{\gamma} \) to produce an electron with energy greater than \( B_e \).
- \( \sigma_p \) is the pair cross section per electron (cm\(^2\)) for a gamma ray of energy \( E_{\gamma} > B_e + 1 \text{ MeV} \).

\[
\lambda = n_e \left[ \sigma_{\text{CO}}(T) + \sigma_p \right]
\]

\( \sigma_{\text{CO}}(T) \) is the total Compton cross section (cm\(^2\)) per electron.

Therefore, the detection efficiency \( (\varepsilon) \) for a scintillator
of length \( L \) (cm), and a discriminator bias \( B_e \) is:

\[
\varepsilon = \frac{J}{J_0} = \frac{\sigma_{co}(\geq B_e) + \sigma_p}{\sigma_{co}(T) + \sigma_p} \left[ 1 - \exp\left( -n_e(\sigma_{co}(T) + \sigma_p)L \right) \right]
\]

This equation, however, neglects self-gating.

The effects of self-gating can be treated in a number of ways. It will be handled here by replacing \( L \) with an effective length, \( L_{\text{eff}} = L - \bar{R}(E_\gamma) \). Here, \( \bar{R}(E_\gamma) \) is the average range of the average energy electron produced by a gamma ray of energy \( E_\gamma \). Some of the gamma rays of energy \( E_\gamma \) can interact within a distance \( \bar{R}(E_\gamma) \) of the back surface and not produce self-gating, while some that interact at a distance greater than \( \bar{R}(E_\gamma) \) will produce self-gating. These two effects will tend to cancel, resulting in an average usable length \( L_{\text{eff}} \).

The average energy transferred to the Compton electron is \( \left( \sigma_a / \sigma_{co} \right)E_\gamma \) where \( \sigma_a \) is the Compton absorption cross section and \( \sigma_{co} \) is the total Compton cross section. Between \( 10 < E_\gamma < 60 \text{ MeV} \), this energy varies from 70% to 80% of \( E_\gamma \). The scattering angle of these electrons is less than \(-15^\circ\) from the direction of the incident photon. In pair production a positron and an electron are produced with total energy (MeV) of \( E = E_\gamma - 1 \ast E_\gamma \). We can consider this as the production of two particles, one less than \( E_\gamma / 2 \) and one greater than \( E_\gamma / 2 \). The higher energy particle is the important one for self-gating. Because of the approximate
equal probability for the high energy particle having any energy between \(E_/2\) and \(E_\gamma\), its average energy will be \(\approx 0.75 E_\gamma\). The average angle between this electron and the incident photon is \(\approx 5^\circ\) for gamma rays greater than 10 MeV. Hence the average high energy electron or positron emitted from either pair or Compton interaction will have an energy \(E_e \approx 0.75 E_\gamma\) and will travel in nearly the same direction as the incident photon.

The range of an electron of energy \(E_e\) is also a rather indefinite thing. Even though in hydro-carbons the energy loss by radiation is neglectable for \(E_e \leq 100\) MeV, there is large straggling due to multiple scattering. Steinberger (1949) has reviewed this problem for the electron energies that are of interest here. The electron is deviated from its original path by an accumulation of very small angle scatterings. For short thickness the distribution in angles is gaussian with a characteristic angle \(<\theta^2>\)

where

\[
<\theta^2> \approx \int_{\chi_1}^{\chi_2} E_e^{-2} dE_e
\]

Because of the \(E_e^{-2}\) dependence, scattering is most important near the end of the electron's range. Steinberger (1949) did a statistical treatment of this scattering for 50 MeV electrons in polystyrene. The result was that the range was reduced by a gaussian shape factor with a most probable range shortening of \(\approx 1.8\) cm and a FWHM of \(\approx 1.3\) cm. This
result is consistent with another treatment of the same problem in aluminum by Fowler et al. (1948). The reduction will not be a strong function of the electron's initial energy because most of the scattering takes place after the electron's energy has dropped to a relatively low value.

The initial electron range \( R_0 \) before corrections for multiple scattering is closely given by the measurable, extrapolated maximum range, \( R_0 = 0.53 E_e - 0.1 \) where \( E_e \) is in MeV and \( R_0 \) is in g/cm\(^2\) (Katz and Penfold, 1952). Therefore, with the density of NE 102 = 1 g/cm\(^3\) and \( E_e = 0.75 E_\gamma \) the effective length of the detector for gamma rays of energy \( E_\gamma \) (MeV) is:

\[
L_{\text{eff}} \text{ (cm)} = L - R_0 (0.75 E_\gamma) - 1.8
\]

\[
= L - (0.4 E_\gamma - 1.9)
\]

Hence, the final gamma ray efficiency for the plastic scintillator, corrected for self-gating is:

\[
\epsilon = \frac{\sigma_{co(>B_e)} + \sigma_p}{\sigma_{co(T)} + \sigma_p} [1 - \exp(-n_e(\sigma_{co(T)} + \sigma_p) L_{\text{eff}})] \quad \text{II-6}
\]

Values for \( \sigma_{co(>B_e)} \), \( \sigma_{co(T)} \), and \( \sigma_p \) for gamma rays up to 30 MeV were taken from Johns et al. (1954). Above 30 MeV they were computed from the tables in X-ray Attenuation Coefficients from 10 keV to 100 MeV (NBS Circular 583, 1957). The electron density in NE 102 is \( 3.4 \times 10^{23} \) electrons/cm\(^3\).

Figure II-8 shows the plastic detector's gamma ray
The calculated gamma ray efficiency of the present plastic detector with no self-gating (Equation II-5) and with self-gating (Equation II-6) for gamma rays entering parallel to the detector's axis.
efficiency for all three bias levels without self-gating (i.e., from Equation II-5). It also shows the efficiency for all three bias levels with self-gating (Equation II-6). These are shown for gamma ray fluxes incident along the detector's axis. Finally, Figure II-9 shows the equivalent isotropic gamma ray sensitivity ($\bar{S}$). This was calculated by integrating the directional sensitivity, $S(\theta, \phi)$, as:

$$\bar{S} = \frac{1}{4\pi} \int_{4\pi} S(\theta, \phi) \, d\Omega$$

Here $S(\theta, \phi)$ is defined as the product of the efficiency at the angle $\theta, \phi$ times the detector's projected area in the direction $\theta, \phi$.

4. CsI(Na) Detector Response

The neutron sensitivity of the CsI(Na) detector is based on measurements at three energies. Dixon (1963) used the pulse shape discrimination properties of CsI to separate out the different charged particle reactions induced by 14.6 MeV neutrons. He determined a cross section of $13 \pm 2$ mb per atom for producing either protons, deuterons, or alpha particles with energies greater than 2.5 MeV. The cross section for production of these charged particles with energies greater than 7.2 MeV was $\leq 4$ mb per atom of Cs or I.

We have done some work in determining the efficiency of CsI in the high energy neutron beam described by Measday.
Calculated gamma ray sensitivities of the present plastic detector for isotropic gamma rays.
(1966). Briefly this neutron beam was produced using the $D(p,n)2p$ reaction. The protons, from the 160 MeV cyclotron at Harvard University, could be degraded in energy to produce a neutron beam with energies between 50-150 MeV. The intensity of the neutron beam was calibrated by counting the $^{11}C$ decay $\beta^+$ particles from the $^{12}C(n,2n)^{11}C$ reaction as discussed by Cumming and Hoffman (1958) and Baranov et al. (1957). This reaction has a threshold of 20.6 MeV and a nearly constant cross section of $\approx 22\text{ mb}$ from $40\text{ MeV} \leq E_n \leq 400\text{ MeV}$. $^{11}C$ is a positron emitter with $T^{1/2} = 20.4\text{ min}$ and $E_{\text{max}} = 0.97\text{ MeV}$. The activated carbon was in the form of an organic (NE 102) plastic scintillator. Hence the $^{11}C$ decay positrons are produced inside the scintillator and can be counted with efficiencies greater than 90%.

A $2'' \times 2''$ NE 102 scintillator with a photomultiplier attached was irradiated in the center of the neutron beam and used to calibrate a large fast counting plastic scintillator that was also in the neutron beam and an ionization chamber that was in the proton beam. Because the rates from the large plastic detector and the ionization chamber tracked at all beam currents, it was felt that this calibration was good at the low beam currents where the CsI detector could be pulse height analyzed. The accuracy of the calibration including counting errors and errors in the $^{12}C(n,2n)^{11}C$ cross section is estimated to be $\approx \pm 15\%$.

The CsI detector was calibrated for pulse height linearity by placing it in the cyclotron proton beam. The
160 MeV proton beam was degraded in energy by calibrated Al absorbers. It was found that the CsI-photomultiplier combination was linear (±5%) up to proton energies of 150 MeV. Protons of 160 MeV would pass entirely through the 2" long CsI.

The CsI detector was placed in the calibrated low intensity neutron beam and pulse height spectrums were taken at 100 and 150 MeV neutron energies. An example of these spectrums are shown in Figure II-10. The energy corresponding to the dip in the spectrum (i.e., channel #10) corresponds to $9 \pm 1$ MeV electron energy equivalent. This was determined by extrapolation from lower energy gamma ray lines. Because of nonlinearities in the response of CsI (Murray and Meyer, 1961) this corresponds to $\approx 6.5$ MeV proton energy equivalent and the broad maximum in the spectrum (channel #16-20) corresponds to a proton energy loss of 10-13 MeV. This maximum can probably be interpreted as the evaporation of single protons from the excited Cs and I nuclei (Dostrovsky et al. 1958). The peaks due to the evaporation of two or more particles are not resolved. The spectrum of emitted charged particles extends up to the full energy of the incident neutron. The cross section for producing pulses greater than 9 MeV electron energy loss equivalent is $330 \pm 100$ mb and $660 \pm 150$ mb respectively at neutron energies of 100 MeV and 150 MeV.

The cross section discussed above at neutron energies of 14.6, 100, and 150 MeV imply, for a 2" x 2" CsI detector,
Figure II-10. The pulse height distributions produced in a 2'' x 2'' CsI scintillator by 100 and 150 MeV neutrons. The dip in the distributions (i.e., channel #10) corresponds to a proton energy loss of \( \approx 6.5 \) MeV.
efficiencies of 0.2\%, 3.3 \pm 1.0\%, and 6.6 \pm 1.5\% respectively. It will be shown next that these efficiencies are much lower than the gamma ray efficiencies and the CsI detector can be considered to be neutron insensitive.

CsI(Na) scintillator is a good gamma ray detector. Cs and I have Z's of 53 and 54, and the density of CsI is 4.5 g/cm$^3$. Gamma rays above 10 MeV interact in CsI mainly through pair production with high efficiency. When using CsI as a "total absorption" (i.e., total absorption of the gamma ray energy) spectrometer, however, certain problems arise. This is a result of the bremsstrahlung or re-radiation of energy by the electrons produced by the original gamma ray. In high Z material like CsI, a high energy electron is soon accompanied by a shower of lower energy secondary photons and even lower energy electrons. The final basic equation governing this process will be stated here. A more complete discussion is given in Chapter 2 of Segre (1964).

The rate of energy loss by fast electrons due to the radiation of photons (i.e., bremsstrahlung) is governed by the equation:

$$-\frac{dE_e}{dx} = \frac{E_e}{X_0}$$

and hence,

$$E_e(x) = E_o \exp\left(-\frac{x}{X_0}\right).$$

II-7

Here, $X_0$ is called the radiation length and is given by:
\[ \frac{1}{X_0} = \frac{4Z^2 n}{137} r_o^2 \ln(183 Z^{-0.33}) \]

where,

\[ n = \text{number of nuclei of charge } Z \text{ per cm}^3 \]
\[ r_o = 2.8 \times 10^{-13} \text{ cm.} \]

Equation II-7 is valid for electron energies where the energy loss due to radiation is larger than that due to ionization. This energy is called the critical energy \( E_c \) and is given by:

\[ \frac{(dE_e/dx)_{\text{rad}}}{(dE_e/dx)_{\text{ioniz}}} = 1 = \text{const } E_c Z. \]

The critical energy for CsI is \( E_c = 11.6 \) and the radiation length \( X_0 \) is 1.85 cm. The CsI detector used in this experiment was 5.1 cm in diameter and 5.1 cm long. The bias levels in electron energy loss were 9±1, 20±2, and 32±3 MeV. Hence bremsstrahlung will be important in the energy range being considered and the detector diameter and length is 2.75 radiation lengths.

Kantz and Hoffstader (1954) have investigated the containment of energy in electron initiated showers in various materials. Their results indicate that for a CsI detector of the size used in this experiment the following fractions of the full electron energy would be contained or dissipated in the detector.

<table>
<thead>
<tr>
<th>( E_e )</th>
<th>Fraction Contained</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 MeV</td>
<td>85%</td>
</tr>
<tr>
<td>41 MeV</td>
<td>70%</td>
</tr>
<tr>
<td>96 MeV</td>
<td>45%</td>
</tr>
<tr>
<td>173 MeV</td>
<td>30%</td>
</tr>
</tbody>
</table>
These values are for an electron of energy $E_e$ incident on the face of the detector. A photon of the same energy would penetrate into the detector some distance before the pair electrons were produced. However, the individual pair electron energy are less than the photon energy and more easily contained. Hence, it appears that for pair events with total energies $\leq 70$ MeV which occur far enough away from the detector end so that self-gating does not occur, only a small fraction of the events, with original energy greater than the bias energy, radiate such a large fraction of their energy that the bias level is not exceeded.

Kantz and Hofstader (1954) also point out that most of the escaping energy is in the form of $\approx 1$ to 5 MeV photons. Higher energy photons do not have a large probability of being emitted and lower energy photons are quickly absorbed by the large photoelectric cross section.

The radiation of energy considerably shortens the range of energetic electrons in CsI. However, the range is still long enough so that self-gating will cause a reduction of efficiency at high gamma ray energies. To calculate this effect we will first assume that the only particles that can cause self-gating are the original pair electrons. This is consistent with Kantz and Hofstader's (1954) statement that most of the escaping energy is in the form of gamma rays. The effects of self-gating will be determined in two ways.

The first method is nearly identical to the method
used for the plastic detector (See Section II-3). That is, the gamma ray is counted only if it interacts in that portion of the detector that is at least a distance, which equals an average electron's range, away from the end of the detector. Hence:

$$
\epsilon_2 = \int_{0}^{L-R_e} \lambda_\gamma >B_e \exp(-\lambda_\gamma l)dl = \frac{\lambda_\gamma >B}{\lambda_\gamma} \left[ 1 - \exp\{-\lambda_\gamma (L-R_e)\} \right] \quad \text{II-8}
$$

where $\lambda_\gamma$ is the inverse mean free path for a photon of energy $E_\gamma$, $L$ is the detector's length, and $R_e$ is the average range for an electron of energy $0.75 E_\gamma$. The average range has been computed by Wilson (1951) and is corrected for radiation and ionization energy losses and multiple scattering.

The second method is discussed by Wilson (1951) and (1952). This author states that the number of electrons ($J$) at a distance $t$ from the place of pair production is given approximately by:

$$
J(t) = 2 \exp(-t/R_\pi)
$$

The characteristic length $R_\pi$ is a function of the initial photon energy $E_\gamma = \frac{W}{E_c} \ln 2$, and $R_\pi$ is given by

$$
R_\pi = \ln 2 \left[ (1 + 1/W) \ln(W + 1) - 1 \right] - R_{\text{m.s.}}
$$
where \( R \) is in radiation lengths, \( R_{\text{m.s.}} \) is a correction due to multiple scattering (\( \approx 0.5 \) radiation lengths for all energies \( \geq E_c \)), and \( W \) is the energy of the photon in shower energy units. Therefore, the probability of at least one electron appearing beyond a distance \( t \) is just

\[
P(t) = J(t) \int_0^\infty J(t') \, dt' = \frac{1}{R} \exp(-t/R) = \lambda \exp(-\lambda t)
\]

where \( \lambda = (R)^{-1} \).

The flux of photons of energy \( E_\gamma \) that interact in the interval \( dt \) at a depth \( t \) is just

\[
dJ = J_0 \lambda (\gamma > B_e) \exp(-\lambda t) \, dt
\]

However, there is a probability \( \lambda \exp(-(L-t)\lambda) \) that at least one of the pair electrons produced in \( dt \) at \( t \) will pass out through the end of the detector (of length \( L \)) and produce self-gating. Hence the efficiency for photons that interact in the detector and do not produce self-gating is just

\[
\epsilon_3 = J/J_0 = \int_0^L \lambda (\gamma > B_e) \exp(-\lambda t) \left[ 1 - \lambda \exp(-\lambda (L-t)) \right] \, dt = \frac{\lambda (\gamma > B)}{\lambda \gamma} \left[ 1 - \exp(-\lambda L) \right] - \frac{\lambda (\gamma > B)\lambda}{\lambda \gamma - \lambda^2} \left[ \exp(-\lambda L) - \exp(\lambda L) \right].
\]

Figure II-11 shows the calculated efficiencies of the Csl detector for gamma rays. Efficiencies \( \epsilon_2 \) and \( \epsilon_3 \).
The calculated gamma ray efficiencies and sensitivities of the present CsI detector. \( \epsilon_1 \) does not include self-gating and was calculated from Equation II-10. \( \epsilon_2 \) and \( \epsilon_3 \) include self-gating and were calculated from Equations II-8 and II-9.
are those calculated by the two methods above. The third efficiency \( \varepsilon_1 \) is that calculated from

\[
\varepsilon_1 = \frac{\frac{\lambda_\gamma (B_e)}{\lambda_\gamma}}{1 - \exp(-\lambda_\gamma L)} \tag{II-10}
\]

and would be the efficiency if there were no self-gating.

Finally, because the length and diameter of the detector are equal, the sensitivity can be assumed to be approximately isotropic. Hence the sensitivity for a gamma ray flux is just the end area (20 cm\(^2\)) times the efficiency given in Figure II-11. Therefore, the sensitivity is \( \approx 11 \text{ cm}^2 \) for 10 MeV \( \leq E_\gamma \leq 70 \text{ MeV} \).
SECTION III

FLIGHT RESULTS

In this section the balloon flights will be described. Also, the dependence of the detector counting rates on atmospheric depth and their variations at balloon float altitude will be presented. Finally, upper limit changes in the counting rates for day-night differences and during solar activity will be calculated.

1. The Balloon Flights

The gondola and the plastic neutron detector were flown, in nearly identical conditions, four times. The CsI detector was used on the first three of these flights. The general aim on all of these flights was to wait for a day of predicted solar activity. The balloon was then launched early in the morning so that it reached its float altitude before sunrise. It was then allowed to float through sunrise and as long as possible into the day.

Details of the four balloon flights are listed in Table III-1. The first flight, 326-P, was terminated at 50K feet because of a defective balloon. The second, 327-P, was delayed at launch because of balloon repairs and did not reach altitude until after sunrise. This flight did, however, remain at float altitude for over ten hours. The last two flights, 364-P and 391-P, worked nearly perfectly
<table>
<thead>
<tr>
<th>Flight and Date</th>
<th>Launch Time</th>
<th>Altitude Time</th>
<th>Cutdown Time</th>
<th>Float Depth</th>
<th>Rigidity Change</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>326-P 18 July 67</td>
<td>0319.0 CDT (UT=EDT-6:00)</td>
<td>----</td>
<td>0426</td>
<td>----</td>
<td>----</td>
<td>Balloon failure at 50 K ft</td>
</tr>
<tr>
<td>327-P 22 July 67</td>
<td>0352.7 CDT</td>
<td>0637</td>
<td>1617</td>
<td>3.9g/cm$^2$</td>
<td>4.9±5.4 GV</td>
<td>No night data</td>
</tr>
<tr>
<td>364-P 2 Nov 67</td>
<td>0238.5 CST (UT=EST-5:00)</td>
<td>0528</td>
<td>1027</td>
<td>3.7g/cm$^2$</td>
<td>4.65±0.05GV</td>
<td>Good flight</td>
</tr>
<tr>
<td>391-P 25 April 68</td>
<td>0257.0 CST</td>
<td>0500</td>
<td>1400</td>
<td>4.1g/cm$^2$</td>
<td>4.7±0.08GV</td>
<td>CsI Detector removed Good flight</td>
</tr>
</tbody>
</table>
in all respects. All of these flights were launched from the National Center for Atmospheric Research (NCAR) balloon base at Palestine, Texas (\(\lambda = 41^\circ\)N).

On each of these flights, NCAR included a 150 pound control package. This contained, among other things, \(\approx 75\) pounds of iron ballast, most of which was normally expended during the flight. The NCAR package was located as far as possible (3 to 10 feet) from the scientific experiments. No effects due to either the package location or ballast dropping were observed. The NCAR package also contained two pressure transducers, both supplied and calibrated by NCAR. One of these, called the "beacon", modulated an RF carrier. The second, called the "photobarograph", was a 0-65 mb Wallace and Tiernan gauge that was photographed every 100-200 seconds. These two units are usually in disagreement at pressures of 4-5 mb. This disagreement can be as much as 0.7 mb and hence, the absolute pressures used later in this paper probably have errors of \(\pm 0.5\) mb. The sensitivity of these transducers to small changes in pressure was not determined, but it appears from the readings supplied to us that it is in the order of 0.2 mb. A pressure change of 0.2 mb would cause a counting rate change of 1-2\% at a depth of \(\approx 4\) mb.

2. Background Counting Rates

The counting rates of all the discriminator levels on both detectors show the expected qualitative dependence
as a function of atmospheric depth. That is, after launch the rates increase with decreasing depth until a maximum near 100 g/cm$^2$ is reached. At still smaller depths the rates decrease, but such that they still appear to have a finite value at zero g/cm$^2$.

The depth dependence of the rates was looked at rather carefully for several reasons. First, these rates provided good flight to flight comparison and showed that the detector properties had not changed. Second, because of the high counting rates certain parameters can be determined with better than normal precision. Last, the different depth dependence of the CsI and plastic detector counting rates can be of some help in our attempts to separate the atmospheric neutron and gamma ray components (See Appendix A).

The counting rates vs. atmospheric depth are shown in Figures III-1 through III-4. In all cases, atmospheric depth is measured in g/cm$^2$ (1.03 g/cm$^2$ = 1 mb) and all rates are five minute averages. The sample error bars shown are derived from the counting statistics alone, (rate/time interval)$^{1/2}$. If a curve has no error bars, then the errors are smaller than the plotted points. Errors in depth are probably less than 1% at depths greater than 50 g/cm$^2$. At depths near float altitude, these errors could be larger than 10%.

The counting rates in the range 200 < x < 800 g/cm$^2$ were fitted by a least square technique to an equation of
Figure III-1. The depth dependence of the plastic detector counting rates. The solid lines are calculated from the coefficients given in Table III-2.
Figure III-2. The depth dependence of the CsI detector counting rates. The solid lines are calculated from the coefficients given in Table III-2.
Figure III-3. The depth dependence of the plastic detector counting rates for depths less than 140 g/cm². The solid lines are calculated from the coefficients given in Table III-3.
Figure III-4. The depth dependence of the CsI detector counting rates for depths less than 140 g/cm². The solid lines are calculated from the coefficients given in Table III-3.
the form \( R(\text{cts/sec}) = A \exp(-x/X_\infty) \). The results of this fitting are shown as solid lines in Figures III-1 and 2, and the characteristic "absorption" length \( X_\infty \) is listed in Table III-2.

**TABLE III-2**

Counting Rate Absorption Lengths in the Atmosphere Between 200 and 650 g/cm\(^2\)

\[
R(x) = R_\infty \exp(-x/X_\infty)
\]

<table>
<thead>
<tr>
<th>Detector</th>
<th>( X_\infty (\text{g/cm}^2) )</th>
<th>( X_\infty (\text{g/cm}^2) )</th>
<th>( X_\infty (\text{g/cm}^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-CPS</td>
<td>168 ± 4</td>
<td>168 ± 5</td>
<td>148 ± 9</td>
</tr>
<tr>
<td>P-D#1</td>
<td>168 ± 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CsI-CPS</td>
<td>157 ± 5</td>
<td>170 ± 4</td>
<td>148 ± 5</td>
</tr>
<tr>
<td>P-D#2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CsI-D#3</td>
<td>153 ± 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-D#3</td>
<td>172 ± 5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At small depths it was found that a linear dependence of the counting rates with depth gave the best fit over the largest depth range. Hence, a least square fit of the form \( R(\text{cts/sec}) = A (1 + bx) \) was made. These results are shown as solid lines in Figures III-3 and 4, and are listed in Table III-3. Note that for this linear approximation, the value of \( A \) is the counting rate at the top of the atmosphere (i.e., \( x = 0 \)).

The float portion of the balloon flight is the most interesting section for it is during this section that any evidence for solar neutrons or gamma rays will be seen. This evidence will, in general, be indicated by a change in counting rate of the various detectors. Unfortunately, there are many phenomena that can cause a change in the detector's
TABLE III-3
COUNTING RATE DEPTH DEPENDENCE BELOW 20 g/cm² OF ATMOSPHERE

\[ R(x) = A (1 + bx) \]

<table>
<thead>
<tr>
<th>Discriminator</th>
<th>A (cts/sec)</th>
<th>b (cm²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-CPS</td>
<td>1334 ± 11</td>
<td>0.036 ± 0.001</td>
</tr>
<tr>
<td>CsI-CPS</td>
<td>320 ± 5</td>
<td>0.033 ± 0.002</td>
</tr>
<tr>
<td>P-D#1</td>
<td>38.4 ± 1.1</td>
<td>0.057 ± 0.002</td>
</tr>
<tr>
<td>P-D#2</td>
<td>16.6 ± 0.5</td>
<td>0.053 ± 0.003</td>
</tr>
<tr>
<td>P-D#3</td>
<td>11.3 ± 0.3</td>
<td>0.053 ± 0.003</td>
</tr>
<tr>
<td>CsI-D#1</td>
<td>4.34 ± 0.15</td>
<td>0.070 ± 0.003</td>
</tr>
<tr>
<td>CsI-D#2</td>
<td>1.76 ± 0.07</td>
<td>0.077 ± 0.004</td>
</tr>
<tr>
<td>CsI-D#3</td>
<td>0.82 ± 0.04</td>
<td>0.076 ± 0.004</td>
</tr>
</tbody>
</table>
counting rate. Some of the known causes are listed below.

1. changes in balloon float depth
2. changes in geomagnetic latitude (i.e., change of cosmic ray threshold rigidities)
3. instrumental and temperature effects
4. delayed solar effects (Forbush decrease)
5. prompt solar effect (polar cap absorption event)

Corrections for 1 and 2 can, in principle, be made exactly. However, the finite sensitivity and accuracy of the pressure indicators allow only approximate corrections. Also, the lack of continuity of both pressure and balloon position readings prevented corrections as accurate as one would wish. The coefficient used for pressure corrections was determined during the ascending portion of each flight. They are listed in Table III-3.

The counting rate dependence on vertical threshold rigidity was investigated during flight 327-P. This flight drifted from a cutoff rigidity of ~4.9 GV to ~5.4 GV. When the pressure corrected counting rates (R) were plotted against the cutoff rigidity (Quenby and Wenk, 1962), the dependence was satisfactorily fitted by \( R = C P^{-n} \), where \( 1.3 < n < 1.5 \) and \( P \) is the vertical cutoff rigidity. Hence, a correction of the form \( \Delta R/R = -1.4 \Delta P/P \) was used to correct the counting rate to a constant rigidity.

The temperature inside the pressure spheres normally drops during the ascending portion of the flight. The minimum temperature of ~5°C is reached approximately at the time
the balloon reaches its float depth. The temperature then increases over the next few hours reaching a stable temperature of ~15-17°C. This temperature range is well within the operational range of the detectors, and no temperature effects were observed or corrections made during any of the flights. Other instrumental checks were made by comparison of the two nearly independent detector counting rates as well as the interflight rates. Also, background tests performed before and after every flight showed that there were no permanent changes in the apparatus.

The Solar-Geophysical Data Tables (U.S. Dept. of Commerce) were inspected closely for geomagnetic effects that could change the detector counting rates. Fortunately, most geomagnetic effects will change the intensity of the charged component of the high altitude radiation field. A solar neutron or gamma ray event, however, will not appreciably change the charged particle shield's counting rate (Alsmiller and Boughner, 1968).

3. Counting Rate Limits for Solar Radiation

The counting rates from all discriminators and the charged particle shields were corrected to a constant depth and cutoff rigidity. They were then plotted against time and inspected for variations. No statistical significant variations that correlated with solar conditions or activity were found. The rates for all detectors while at float are shown in Figures III-5 through III-10. All the data shown
has been corrected to a constant depth (the average depth for that particular flight) as indicated on each figure, and all data points are five minute averages. The sample error bars are the computed standard deviation, \( \sigma_{\text{com}}(R_i) = \left( \frac{1}{n} \sum (R_i - \bar{R})^2 \right)^{1/2} \). Here \( R_i \) is the ith five minute average counting rate, \( n \) is the number of five minute averages during float, and \( \bar{R} = \frac{1}{n} \sum R_i \). Figure III-5 shows a sample of the data from flight 327-P that has not been corrected for rigidity changes. The rigidity dependence, as discussed before, is indicated by a solid line. Figures III-6 through 10 have been corrected to a constant rigidity cutoff (again the average for that particular flight) as indicated on each figure.

The computed standard deviation for some of the discriminator levels on all of the flights are larger than the standard deviation derived from counting statistics \((\sqrt{R/T})\) alone. This will be discussed more fully later.

The continuous emission of high energy solar neutrons was investigated by comparing the "night" and "day" counting rates. The mean free path for high energy neutrons in the atmosphere is approximately 80 g/cm\(^2\) (Alsmiller and Boughner, 1967). Hence, "night" was defined as that portion of the float period when there was more than 125-150 g/cm\(^2\) of atmosphere between the detector and the sun. The average atmospheric thickness during the "night" was greater than \(10^3\) g/cm\(^2\). Similarly, "day" was defined as that portion of the float when there was less than 20 g/cm\(^2\) of atmos-
Some counting rates at balloon float corrected to an atmospheric depth of 3.9 g/cm$^2$ but not corrected for vertical cutoff rigidity changes. The solid lines show the calculated rigidity dependence with a $P^{-1.4}$ rigidity dependence. The solid was normalized to the data at 1200 (CDT). The rigidity change in the time interval shown was $4.9 < P < 5.3$ Gv. The open circles at the bottom of the figure indicate when the tracking airplane recorded a balloon position reading. The vertical cutoff rigidity as a function of time was determined from these. The closed circles indicate the times of recorded ballast dropping. Note how these correlate with the small increases in counting rate that can be seen on P-CPS.
Flight 327

TIME

0600 0800 1000 1200 1400 1600 (CDT)

Rates (counts/sec)

1500 1480 1460 1440 1420 1400 1380 1360 1340 1320 1300

P-CPS

P-D #1

Airplane position readings

Ballast dropping

Figure III-5
Figure III-6. Counting rates of the plastic detector for Flight 327-P corrected to 3.9 g/cm² and 5.06 GeV. The information at the bottom of the figure shows the "day" time interval and the times of different types of solar activity. Each point represents a five minute average and the error bars correspond to one computed standard deviation. The length enclosed by the arrows represents a 2% change in the counting rate.
Figure III-7. Counting rates of the CsI detector for Flight 327-P corrected to 3.9 g/cm² and 5.06 Gv. The information at the bottom of the figure shows the "day" time interval and the times of different types of solar activity. Each point represents a five minute average and the error bars correspond to one computed standard deviation. The length enclosed by the arrows represents a 2% change in the counting rate.
Figure III-8. Counting rates of the plastic detector for Flight 364-P corrected to 3.7 g/cm² and 4.6 Gv. The information at the bottom of the figure shows the "day" and "night" time intervals and the times of different types of solar activity. Each point represents a five minute average and the error bars correspond to one computed standard deviation. The length enclosed by the arrows represents a 2% change in the counting rate.
Figure III-9. Counting rates of the CsI detector for Flight 364-P corrected to 3.7 g/cm² and 4.6 Gv. The information at the bottom of the figure shows the "day" and "night" time intervals and the times of different types of solar activity. Each point represents a five minute average and the error bars correspond to one computed standard deviation. The length enclosed by the arrows represents a 2% change in the counting rate.
Figure III-10. Counting rates of the plastic detector for Flight 391 corrected to 4.1 g/cm² and 4.7 Gv. The information at the bottom of the figure shows the "day" and "night" time intervals and the times of different types of solar activity. Each point represents a five minute average and the error bars correspond to one computed standard deviation. The length enclosed by the arrows represents a 2% change in the counting rate.
phere between the detector and the sun. The average "day" thickness was 10-15 g/cm². The "day" and "night" time intervals were determined by calculating, from geometric arguments, the angle between the vertical and the sun as a function of time. The air mass between the detector and the sun can be found if this angle is known (Pressly, 1952).

The rates during the "night" and "day" intervals for flights 364-P and 391-P are given in Table III-4. The errors given in this table are the computed standard deviations for the average rate $\sigma_{\text{com}}(\bar{R})$ during the "day" or "night" interval. That is, the error given is $\sigma_{\text{com}}(\bar{R}) = \left[ \frac{1}{n(n-1)} \sum (\bar{R} - R_i)^2 \right]^{1/2}$, where $R_i$ is the ith five minute average out of the n independent averages in the "day" or "night" interval and $\bar{R} = \frac{1}{n} \sum R_i$. From the table we can see that the difference ($\Delta$) between the "day" and "night" mean counting rates ($\Delta = \bar{R}_D - \bar{R}_N$) is approximately equal to or less than the computed standard deviation of the difference, $\sigma(\Delta) = [\sigma^2(\bar{R}_D) + \sigma^2(\bar{R}_N)]^{1/2}$. The exceptions to this are the differences from the two highest discrimination levels for the plastic detector (P - D#2 and P - D#3) on Flight 391-P. The rates from these two discrimination levels imply that the high energy neutral intensity was higher during the night than during the day. This effect seems to be real, but its explanation is not known. Note, however, that the lowest discrimination level (P-D#1) showed no "day" - "night" difference.

These results indicate that there is little signifi-
TABLE III-4

"DAY" - "NIGHT" COUNTING RATE DIFFERENCES AND UPPER LIMIT COUNTING RATES FOR CONTINUOUS SOLAR EFFECTS

<table>
<thead>
<tr>
<th>Flight and Detector</th>
<th>&quot;Day&quot; Rate (cts/sec)</th>
<th>&quot;Night&quot; Rate (cts/sec)</th>
<th>Difference (cts/sec)</th>
<th>Upper Limit Continuous Solar Effect (cts/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>364-P</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCPS</td>
<td>1484 ± 3</td>
<td>1452 ± 4</td>
<td>+32 ± 5</td>
<td>----</td>
</tr>
<tr>
<td>P D#1</td>
<td>42.59 ± 0.07</td>
<td>42.85 ± 0.22</td>
<td>-0.26 ± 0.23</td>
<td>0.70</td>
</tr>
<tr>
<td>P D#2</td>
<td>18.04 ± 0.06</td>
<td>18.22 ± 0.11</td>
<td>-0.18 ± 0.12</td>
<td>0.40</td>
</tr>
<tr>
<td>P D#3</td>
<td>11.92 ± 0.04</td>
<td>12.01 ± 0.08</td>
<td>-0.09 ± 0.09</td>
<td>0.30</td>
</tr>
<tr>
<td>CsI CPS</td>
<td>350.5 ± 0.7</td>
<td>344.6 ± 0.8</td>
<td>+5.9 ± 0.9</td>
<td>----</td>
</tr>
<tr>
<td>CsI D#1</td>
<td>5.16 ± 0.02</td>
<td>5.13 ± 0.11</td>
<td>+0.03 ± 0.11</td>
<td>0.33</td>
</tr>
<tr>
<td>CsI D#2</td>
<td>2.07 ± 0.02</td>
<td>2.12 ± 0.03</td>
<td>-0.05 ± 0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>CsI D#3</td>
<td>0.956 ± 0.010</td>
<td>0.979 ± 0.017</td>
<td>-0.023 ± 0.020</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>391-P</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCPS</td>
<td>1481 ± 1.5</td>
<td>1462 ± 1.4</td>
<td>+19 ± 2</td>
<td>----</td>
</tr>
<tr>
<td>P D#1</td>
<td>43.44 ± 0.07</td>
<td>43.39 ± 0.12</td>
<td>+0.05 ± 0.14</td>
<td>0.42</td>
</tr>
<tr>
<td>P D#2</td>
<td>18.05 ± 0.04</td>
<td>18.68 ± 0.05</td>
<td>-0.63 ± 0.06</td>
<td>0.85</td>
</tr>
<tr>
<td>P D#3</td>
<td>12.63 ± 0.03</td>
<td>13.17 ± 0.06</td>
<td>-0.59 ± 0.07</td>
<td>0.70</td>
</tr>
</tbody>
</table>
cant bias or systematic error introduced by our corrections for rigidity and pressure changes. The information in Table III-4 also indicated that (except for P-D#2 and #3 of Flight 391-P) there is no statistically significant differences between the "day" and "night" counting rates. From this we can state that at a 95% confidence level, any continuous flux from the sun must have contributed less $\pm 3\sigma(\Delta)$ during each flight. This rate is given in Table III-4 under the column "Upper Limit Continuous Solar Effect". The upper limits given for P-D#2 and #3 for Flight 391-P include the real differences observed.

The upper limit counting rate changes for the impulsive emission of solar neutrons in association with solar activity or flares was also investigated. As stated earlier, L & R's work suggests that there would be a rather unique signature for an impulsive solar neutron event. This would be an increase in the plastic detector counting rate, unaccompanied by any increase in the charged particle shield rates. The plastic detector rates would also relatively quickly return to their pre-event background levels. Hence, short term impulsive increases in the plastic detector counting rates must be looked for that are not accompanied by a comparable increase in the charged particle shield counting rates.

Table III-5 lists the average computed standard deviation for each five minute interval $[\sigma_{\text{com}}(R_i)]$ during the day portion of flights 327-P, 364-P, and 391-P. This
The computed standard deviation is given by

\[ \sigma_{\text{com}}(R_i) = \left\{ \frac{(n-1)}{2} \sum \left( R_0 - R_i \right)^2 \right\}^{1/2} \]

L & R's calculations indicate that the minimum time duration of a solar neutron event at 1 A.U. is \( \approx 10^3 \) seconds. Hence, at least four consecutive five minute averages would be affected by any solar neutron events. Now, there is a less than 2% probability that a change in counting rate of magnitude \( 3/\sqrt{4} \sigma_{\text{com}}(R_i) \) over a 20 minute period can be accounted for by counting statistics alone. Hence, this rate can be used to set a limit on the impulsive emission of solar neutrons. This upper limit rate is listed in Table III-5 under the column "Upper Limit Impulsive Solar Effects".

Because solar gamma ray events at 1 A.U. are not necessarily spread out in time, only the variations for a five minute interval were used. Therefore, in Table III-5, for the CsI detector, \( 3 \sigma_{\text{com}}(R_i) \) is given for the "Upper Limit Impulsive Solar Effect".

The Solar Geophysical Data Tables were inspected for solar activity during the float interval for each flight. There was a solar flare patrol during every flight and the start time of observed solar flares are recorded on the bottom of Figures III-6 through 10. Sub flares are indicated by dots and the larger flares by their optical importance. The average Kp index during Flight 327 was 1 and there were several small X-ray events seen between 14:57-
## TABLE III-5

"DAY" COUNTING RATE VARIATIONS AND UPPER LIMIT COUNTING RATES FOR IMPULSIVE SOLAR EFFECTS

<table>
<thead>
<tr>
<th></th>
<th>Day Rate (cts/sec)</th>
<th>Computed Standard Deviation for 5 min. Average (cts/sec)</th>
<th>Upper Limit Impulsive Solar Effect (cts/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FIT 327</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-D#1</td>
<td>44.1</td>
<td>± 0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>P-D#2</td>
<td>18.3</td>
<td>± 0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>P-D#3</td>
<td>12.4</td>
<td>± 0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>CsID#1</td>
<td>5.10</td>
<td>± 0.15</td>
<td>0.5</td>
</tr>
<tr>
<td>CsID#2</td>
<td>2.10</td>
<td>± 0.10</td>
<td>0.5</td>
</tr>
<tr>
<td>CsID#3</td>
<td>0.97</td>
<td>± 0.05</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>FIT 364</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-D#1</td>
<td>42.6</td>
<td>± 0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>P-D#2</td>
<td>18.0</td>
<td>± 0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>P-D#3</td>
<td>11.9</td>
<td>± 0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>CsID#1</td>
<td>5.16</td>
<td>± 0.15</td>
<td>0.5</td>
</tr>
<tr>
<td>CsID#2</td>
<td>2.06</td>
<td>± 0.15</td>
<td>0.5</td>
</tr>
<tr>
<td>CsID#3</td>
<td>0.96</td>
<td>± 0.07</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>FIT 391</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-D#1</td>
<td>43.4</td>
<td>± 0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>P-D#2</td>
<td>18.0</td>
<td>± 0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>P-D#3</td>
<td>12.6</td>
<td>± 0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
During Flight 364-P the Kp index was 2, and the satellite Explorer 34 observed a low energy (< 60 MeV) proton event, beginning just before the balloon reached float at approximately 10:00-11:00 UT. This event continued throughout the day. It was apparently associated with an IB flare that occurred just as the balloon was launched. The sun was very quiet during Flight 391-P, the Kp index being 1- and only subflares were observed.

In spite of our best efforts, none of the flight days can be considered an active solar day. None of the 15 flares of importance > _ 1F observed during the three flights had an observable proton event associated with it.

There were two impulsive increases in the plastic detector's counting rate, however. These increases occurred around 09:20 and 11:40 CDT on Flight 327-P (See Figures III-5, 6, and 7). Note, however, that these increases are also evident on the charged particle shield rates. Although there were no pressure changes recorded during this period, closer inspection of the NCAR flight data showed that ballast was dropped at this time. The times of ballast release are indicated on Figure III-5. Apparently the NCAR operator upon noticing a decrease in altitude, proceeded to drop ballast until the correct or float altitude was reached. Only this final pressure was recorded leaving no indication of a pressure change except for ballast dropping. Hence, these increases are most likely due to a change in the balloon's float altitude.
It is interesting to compare the rate increase for one of these serious events with the upper limit impulsive rates given in Table III-5. For example, consider the plastic discriminator #1 (P-D#1) counting rate increase that was centered at approximately 09:20 CDT. This event covered the 45 minute period between 09:00 and 09:45 during which the average counting rate was 44.48 cts/sec. The average background rates during the one hour periods before and after this event were 43.49 and 43.59 cts/sec, respectively. Hence this event consisted of an excess of $\approx 0.94$ cts/sec over the 45 minute period. From Table III-5 the counting rate excess needed at a 98% confidence level over a 20 minute period is 1.2 cts/sec. Hence, this event, if it had occurred in association with other solar activity and without a charged particle shield rate increase, would have been taken as only tentative evidence of an impulsive solar neutron event.

It was pointed out earlier that the computed standard deviation of the counting rates was always higher than that expected from counting statistics alone. This is especially noticeable on the discrimination levels with higher counting rates. These excess variations can be easily observed in Figures III-6 to 10. A quantitative test of these variations can be made by use of the Chi-square test (Evans, 1955, Chap. 27). For example, the probability of the P-D#1's counting rate variations being as large as they are from counting statistics alone is less than 0.5%. Hence,
they are undoubtedly real.

The cause of these excess variations are not known with certainty. However, they may be due to the lack of sensitivity of the pressure indicators. During ascent, the balloon's climb rate is \(-10^3\) ft/min. At a depth of 4 g/cm\(^2\) this corresponds to a change of \(-0.15\) g/cm\(^2\)/min. A pressure change of 0.15 mb would probably not be seen by the pressure indicators and it is large enough to cause counting rate variations of \(\pm 1\%\). It is known that a balloon's altitude is affected by the reflectivity of the surface it is passing over, and the balloon could be oscillating about a constant float pressure. Another possibility is that the intensity of the high altitude radiation is not constant. It may have variations in the order of 1% over a period of a few minutes most of the time. Better pressure indicators will have to be used before this question can be resolved. Fortunately, these small uncorrected variations make very little difference in the lower flux limit that can be set.

Let us briefly summarize the main results of this section. Upper limit counting rates have been set for both the long time intervals characteristic of continuous emission of solar radiation and for the short time intervals characteristic of impulsive solar emission. These limits are, in general, not dependent upon the absolute value of the "background" counting rate. They depend only on any long term bias and the variations or fluctuations in this
background. In other words, this is a differential measurement. The counting rate limits that have been set give the smallest statistically significant counting rate change that can be seen. These rates will be converted into upper limit neutron and gamma ray fluxes and compared with the results of other experiments in the next section.
SECTION IV

INTERPRETATIONS AND CONCLUSIONS

1. Upper Flux Limits for Solar Radiation

To be useful, the upper limit counting rates given in the last section must be expressed as an equivalent upper limit neutron flux. Note that even if an event did occur, such that these limits were exceeded, it would still be necessary to show that it was caused by solar neutrons. As stated earlier, this would be done by comparison of the plastic and CsI detector and the charged particle shield rates, as well as time correlation with solar activity. However, the lack of such an event allows us to place upper limits on the solar neutron flux or on the neutron flux from any other source in the sky.

In order to determine the flux limit, both a detector response function and an assumed neutron energy spectrum are needed. The energy dependent neutron response for the detectors is given in Section II. The spectrum used was the solar neutron energy spectrum at 1 A.U., given by L & R. Their spectral shape is based on the assumption that the charged particle spectrum, $\frac{dJ}{dP}$ (protons/cm$^2$ sec MV), at the sun is of the form $\frac{dJ}{dP} = J_0 \exp(-P/P_0)$. Here, $P$ is the charged particle rigidity and $P_0$ is a characteristic rigidity. The characteristic rigidity of SEP's at the earth
normally ranges from 50 to 200 MV. The solar neutron spectral shape, \( N(E_n, P_0) \) (taken from L & R, Figure 26) and normalized so that \( \int_0^\infty N(E_n, P_0) dE_n = 1 \), where \( E_n \) is the neutron energy, is shown in Figure IV-1 for \( P_0 = 60, 125, \) and 200 MV. It is interesting to note that - 98% of the neutrons at 1 A.U. fall below 100 MeV if \( P_0 = 60 \) MV. These fractions for 125 and 200 MV are 65% and 40%.

Consider now a differential solar neutron flux, \( \frac{dF_s}{dE_n} = k N(E_n, P_0) \), incident on the plastic detector. This would give a counting rate \( (R) \) of

\[
R = \int_0^\infty S(E_n) \cdot k N(E_n, P_0) dE_n \quad IV-1
\]

where \( S(E_n) \) = energy dependent response (or sensitivity) of the plastic detector in counts per sec per unit flux incident on the detector (cm\(^2\))

\( k = \) a normalizing factor with units of neutron/cm\(^2\) sec

and the other terms are defined above. If we replace \( R \) in Equation IV-1 with \( \delta \), the upper limit counting rate, then we can evaluate the upper limit solar neutron flux as

\[
k \leq \frac{\delta}{\int_0^\infty S(E_n) N(E_n, P_0) dE_n} \quad IV-2
\]

The evaluated term \( k \) is just the integral upper limit solar neutron flux.

Equation IV-2 was numerically integrated using the
Figure IV-1. The solar neutron spectral shape at 1 A.U. [N(E_n, P_o)] for the solar charged particle characteristic rigidities, P_o = 60, 125, and 200 MV. The shape was taken from Figure 26 in Lingenfelter and Ramaty (1967) and normalized such that

\[ \int_0^\infty N(E_n, P_o) dE_n = 1 \]
counting rate limits given in Tables III-4 and 5 and the neutron sensitivity functions shown in Figure II-7. The results of this integration are shown in Tables IV-1 and 2.

**TABLE IV-1**

Upper Limit Integral Fluxes for Continuous Emission of Solar Neutrons

<table>
<thead>
<tr>
<th>Bias Levels</th>
<th>Characteristic Rigidities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_0 = 60\text{ MV}$</td>
</tr>
<tr>
<td>P-D#1</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>(neut/cm$^2 \text{ sec}$)</td>
</tr>
<tr>
<td>P-D#2</td>
<td>$2.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>P-D#3</td>
<td>$2.9 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

**TABLE IV-2**

Upper Limit Integral Fluxes for Impulsive Emission of Solar Neutrons

<table>
<thead>
<tr>
<th>Bias Levels</th>
<th>Characteristic Rigidities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_0 = 60\text{ MV}$</td>
</tr>
<tr>
<td>P-D#1</td>
<td>$2.8 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>(neut/cm$^2 \text{ sec}$)</td>
</tr>
<tr>
<td>P-D#2</td>
<td>$4.1 \times 10^{-2}$</td>
</tr>
<tr>
<td>P-D#3</td>
<td>$4.8 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Table IV-1 shows the integral upper limit fluxes (i.e., the $k$'s) for the continuous emission of solar neutrons. These are shown for each of the three bias levels and for three assumed characteristic rigidities or neutron spectral shapes. Similar upper limits for the impulsive emission of
solar neutrons are shown in Figure IV-2. Note that these
two tables show that somewhat smaller limits can be set
with the lower bias levels and for events with low character-
istic rigidities. However, the upper limits that can be
set are not a strong function of either of these parameters.

It is more convenient to compare the present results
with other experimental and theoretical results when the
upper limit solar neutron spectrum is shown in a differen-
tial form. To obtain the equivalent differential upper
limit flux, merely multiply the k's given in Tables IV-1
and 2 by the $N(E_n P_0)$ given in Figure IV-1. A sample dif-
ferential spectrum for the continuous emission (Plastic
Detector-Disc #1 and $P_0 = 60$ MV) is indicated as Present
Experiment in Figure IV-2. Also shown in Figure IV-2 are
three other experimental upper limit spectrums, two theoret-
ical estimates of the quiet sun upper limits and results
of two reported observations of solar neutrons.

The OSO-1 experiment conducted in 1962 from an
earth orbiting satellite (Hess and Kaifer, 1967) used a
moderated $BF_3$ neutron counter. This experiment provided
continuous monitoring of the sun over approximately 1500
diurnal periods. An upper limit of less than $2 \times 10^{-3}$
neutrons/cm$^2$ sec in the energy range $10$ keV$<E_n<10$ MeV was
set. We have transformed this result into the differential
spectrum shown in Figure IV-2 assuming a power law neutron
spectrum shape in the energy region indicated. The Vela
satellite experiment (Bame and Asbridge, 1966) used a
Figure IV-2. Upper limit differential spectrums at 1 A.U. for the continuous emission of solar neutrons from the quiet sun. See text for discussion and references.
moderated He\textsuperscript{3} neutron counter. During the time interval 1964-65 an upper limit on the diurnal variations in the detector counting rate was set at 0.1 cts/sec. Using this limit and integrating the published Vela detector sensitivity multiplied by the theoretical solar neutron spectral shape for $P_0 = 60$ MV over all neutron energies gives the result shown in Figure IV-2. The Minnesota experiment conducted in 1964 (Webber and Ormes, 1967) utilized a charged particle telescope sensitive to secondary protons in the energy range 60-320 MeV. This experiment was flown on a balloon such that there was 12.9 g/cm\textsuperscript{2} of atmosphere between the sun and the detector. The telescope periodically viewed the sun through this atmosphere as the detector was rotated. It was deduced from these measurements that not more than $10^{-4}$ protons cm\textsuperscript{-2} sec\textsuperscript{-1} ster\textsuperscript{-1} in the energy range 60-320 MeV could have been produced by solar neutrons interacting in the atmosphere between the detector and the sun. An energy dependent efficiency was used by these authors to obtain the upper limit spectrum shown in Figure IV-2. It should be noted, however, that the efficiency used by these authors appears to be considerably higher than that indicated by Monte Carlo calculations (Alsmiller and Boughner, 1967). In these calculations it was assumed that high energy solar neutrons were incident on the top of the atmosphere. The flux of secondary neutrons and protons was then calculated at different depths in the atmosphere. It was found that 100 MeV and 150 MeV neutrons produced protons with energy
greater than 25 MeV at a depth of 10 g/cm\(^2\) with an efficiency of 0.03\% and 0.1\% respectively. These efficiencies are a factor of 10 smaller than those used by Webber and Ormes (1967); hence, their limit as indicated in Figure IV-2 may be too low.

The measurement labeled Tata (1962) in Figure IV-2 was a balloon borne emulsion experiment (Apparao et al., 1966) conducted in 1962. In this experiment the ratio of the downward neutron flux to the upward neutron flux was deemed too large, and the excess downward flux was attributed to solar neutrons. The measurement indicated by Tata (1966) was made by using a scintillator-spark chamber detector in 1966 (Daniel et al., 1967). This detector experienced an unusual increase in the event rate after the balloon borne instrument had reached its float altitude. The increase was attributed to solar neutrons associated with a sub-flare that occurred several hours later. The interpretation of both of these experiments has been questioned by Hess and Kaifer (1967) and Holt (1967).

Theoretical upper limits for the solar neutron flux were obtained by Roelof (1966) based on IMP 1 proton measurements of MacDonald and Ludwig (1964). He assumed all observed protons in the energy interval 15-75 MeV were produced by solar neutron decay. In Figure IV-2 the upper limit marked Roelof No Piff., (1964) would be the flux of undecayed solar neutrons at 1 A.U. if the decay protons suffered no diffusion in the interplanetary magnetic fields;
and the lower curve, marked Roelof (Diff., 1964), would be the flux if the protons did suffer isotropic diffusion.

Two other experimental results not shown on Figure IV-2 should also be noted. Kim (1967) has reported results from a 10 hour exposure on July 30, 1966, of two emulsion stacks. One of these stacks was always pointed toward the sun and the other away. Comparison of the two stacks has yielded, in the energy interval 20-100 MeV, a solar neutron flux of $1.1 \times 10^{-2}$ neutrons cm$^{-2}$ sec$^{-1}$ with an upper limit of $2.8 \times 10^{-2}$ neutrons/cm$^2$ sec. Complete scanning of the emulsions will reduce the large statistical errors and determine if the apparent real flux remains. Kim's (1967) limit of $2.8 \times 10^{-2}$ neutrons/cm$^2$ sec is nearly the same as that obtained in this experiment. Hence his limit if shown on Figure IV-2 would be identical to that indicated as Present Experiment.

Zych (1968) has reported the results of a search for solar neutrons on July 28, 1967, with a spark chamber. It was hoped that the energy and direction of recoil protons generated in a hydrocarbon radiator could be observed in the spark chamber. One fourth of the radiator was graphite so that carbon effects could be observed. The flight showed that as many protons were emitted from the carbon sector of the radiator as from the hydrocarbon sector. This result was unexpected. It indicated that in the energy region 20-100 MeV, the proton producing cross sections in carbon and aluminum are much larger than that in hydrogen. Because
the cross sections and kinematics for these reactions are not known, the information obtained from an individual proton recoil cannot be used to determine the incident neutron's direction and energy. At any rate, no evidence of solar neutrons was observed. After making some assumptions about cross sections, an upper limit flux in the energy interval 20-100 MeV of $5 \times 10^{-3}$ neutrons cm$^{-2}$ sec$^{-1}$ was set. This limit was for impulsive emission during two importance solar flares. No limit was set for the continuous or steady state emission.

There are fewer reported results for limits on the impulsive emission of neutrons. The reason for this is, of course, because of the difficulty of having a suitable detector at the right place during solar activity. In discussing the limits on impulsive emission it is both common and convenient to give these limits as a fraction of the total flux expected from the great flare of 12 November 1960. The predicted number of secondaries from this flare were treated in detail by L & R and some of their results will be given here. The total number of particles released from the sun was stated to be $6 \times 10^{34}$ protons greater than 30 MeV. The characteristic rigidity ($P_o$) of these charged particles was $125$ MV. If all of the accelerated charged particles escaped from the sun (i.e., none slowed down and stopped in the photosphere) and if they passed through 1-4 g/cm$^2$ of neutral solar atmosphere while being accelerated, then L & R calculate a peak flux at
l A.U. of 3 to 12 neutrons/cm² sec. If only one half of the total accelerated particles escaped then they calculate a peak flux at 1 A.U. of 5-24 neutrons/cm² sec from the acceleration phase, and 33 neutrons/cm² sec from the slowing down phase. For comparison's sake the latter is assumed to be true and the 12 November 1960 flare is semi-defined as having produced a peak neutron flux at 1 A.U. of ≈ 60 neutrons/cm² sec.

The Vela neutron detector (Bame and Asbridge, 1966) has probably observed more solar flares than any other, all with negative results. The largest flare for which results have been published was the flare on 2 September 1966 (Bame et al., 1967). The upper limit set for this flare was -2 neutrons/cm² or -3% of the 12 November 1960 flux.

The 12 September 1966 flare produced at 1 A.U. a time integrated flux greater than 25 MeV of -2 x 10⁸ proton/cm². These protons had a characteristic rigidity of -60 MV at 1 A.U. L & R estimated that this flux implied that -6 x 10³³ protons escaped from the sun during the flare. The peak neutron flux at 1 A.U., assuming one half of the charged particles were stopped on the sun, was calculated by L & R to be -0.5 neutrons/cm² sec or somewhat less than 1% of the 12 November 1960 flare. Hence, the Vela limit stated above, is not inconsistent with L & R's calculations. However, the Vela limits for this flare do indicate that L & R's flare model and calculations are an upper limit estimate for neutron emission during solar activity. The
OSO-1 neutron detector (Hess and Kaefer, 1967) has also observed a number of solar flares, again with negative results.

The upper limit impulsive neutron flux at 1 A.U. that can be set with the present detector has been conservatively determined to be between 0.05 to 0.10 neutrons/cm$^2$ sec. This assumes an event duration at 1 A.U. of $-10^3$ seconds and is for the energy range $15 < E_n < 120$ MeV. This limit represents an event - 0.1 - 0.2% the size of the one calculated for the 12 November 1960 flare. Hence, the predicted flux from the 2 September 1966 flare is five times this limit and could have been easily seen with the present detector.

As stated earlier, none of the flares that occurred during the three flights were especially large and none had known SEP events associated with them. Hence, a direct test of L & R's flare model and calculations cannot be made. However, during the three flights there were 15 flares of optical importance greater than 1F, while 9 were greater than 1B and the largest was 2N. It may be interesting to make some statistical speculations based on the negative results from these flares.

We have sampled nine solar flares of importance, 1B-2N for the emission of neutrons. None of these were in fact associated with a flux at 1 A.U. as large as 0.1 neutron/cm$^2$ sec. Hence we can ask what does this sample allow us to say about the infinite number of solar flares
of the same size? Limits on the probability of an average flare to emit neutrons \((p)\) can be made with the binomial probability distribution

\[
P_r^n = \frac{n!}{r!(n-r)!} \ p^r \ (1-p)^{n-r}
\]

where:  
\(n\) = total number of samples (i.e., number of flares observed)  
\(p\) = fraction of total population which has the quality we are looking for (i.e., flares which emit neutrons)  
\(r\) = number out of the \(n\) samples observed which did have quality being looked for (i.e., number of neutron events observed)  
\(P_r^n\) = probability of \(r\) successes out of \(n\) samples with a given \(p\) from a known \(n\) and \(r\) (See Wilson, 1952, Chap. 8.6)

If we set \(P_r^n = 5\%\), then with \(n = 9\) flares and \(r = 0\) neutron events observed, we can state at a 95\% confidence level that less than 28\% of all flares of this size can be associated with a neutron event. That is, the binomial probability distribution states that there is still a 5\% chance of us observing no neutron events during the nine flares even if on the average of as many as 28\% of all such flares do emit neutrons. The above statement does not, of course, provide any information on the specifics of an individual flare or neutron event. It will, however, allow us to make further
comparison of these results with those on charged SEP's near 1 A.U. It may also provide some information on the course of action for future experiments.

To make a comparison with SEP results we must first determine what proton flux this neutron limit implies. This can be estimated from the calculated results of the 2 September 1966 event discussed earlier and the measured proton flux for the same flare (Bostrom et al., 1967). These indicate that a flux of 0.1 neutrons/cm$^2$ sec at the earth would imply a peak flux of $J_p (> 25$ MeV) $\approx 10^3$ protons/cm$^2$ sec. Recall that this is based on $\approx 50\%$ of the SEP's escaping from the sun.

It may also be interesting to note that even if all of the accelerated SEP's are trapped and stopped at the sun, there must still be a flux of proton at 1 A.U. This is due to the neutron-decay protons that are produced between the sun and the earth. Roelof (1966) has shown that because of diffusion of protons in the interplanetary magnetic field, a flux of 0.1 neutrons/cm$^2$ sec implies a flux of 20-50 proton/cm$^2$ sec at 1 A.U. from this source alone.

McCracken et al. (1967) state that 80\% of all flares of importance greater than 2B produce detectable SEP events. However, the detector they used had a threshold of only 7.5 MeV. Hence there are two corrections that must be made to the above data for our use. One is to correct for the fact that the peak flux is seen only if the satellite and the flare event are in the same magnetic coupling domain. The
second is needed to go from a threshold of 7.5 to one of 25 MeV. These two corrections tend to cancel, and let us assume for lack of better information that they do. Then, out of the sixteen flares of importance greater than 2B that McCracken et al. (1967) observed, only four had a flux in the order of $10^3$ protons/cm$^2$ sec. From this we can again say at a 95% confidence level that between 8 and 55% of all flares greater than 2B produce sufficiently large SEP events to yield a flux at 1 A.U. greater than 0.1 neutrons/cm$^2$ sec. The present results, stated above, are not inconsistent with this. The fact that McCracken et al. (1967) were observing somewhat larger flares than were observed in the present experiment, indicates that future experiments should strive even more to observe the largest possible flares.

The final item to be discussed in this section are the upper limits on the solar gamma ray spectrum. These measurements were made with the CsI detector and the upper limit counting rates are given in Tables III-4 and 5. The gamma ray sensitivity, $S(E_\gamma)$, can be taken as a constant 11 cm$^2$ for the lowest discrimination level and for gamma rays between 15 to 70 MeV. The high energy gamma ray spectra from neutral pion decay shows a broad flat maxima (L & R) centered about 70 MeV. To a first approximation, this can also be taken as independent of energy. Hence, with an upper limit counting rate of 0.33 cts/sec, the maximum continuous gamma ray flux, $F_{\text{min}}$, is:
in the energy interval 15 to 70 MeV. Similarly, the upper limit impulsive gamma ray flux is $5 \times 10^{-2}$ gamma rays/cm$^2$ sec in the same energy range. The limit for the continuous flux may be compared with earlier balloon nuclear emulsion measurements. These were by Frye et al. (1966) at 11 g/cm$^2$ in early 1959 and by Fichtel and Kniffen (1965) at 4.7 g/cm$^2$ in 1963. The limits were respectively $2.8 \times 10^{-2}$ gamma rays/cm$^2$ sec for $E_\gamma > 20$ MeV, and $1.5 \times 10^{-3}$ gamma rays/cm$^2$ sec for $10 < E_\gamma < 50$ MeV.

It is interesting to note that the gamma ray flux in this energy interval from the 2 September 1966 flare was estimated by L & R to be $2.5 \times 10^{-2}$ gamma rays/cm$^2$ sec. This assumes that 50% of the SEP's escape and that the event duration is $\approx 300$ sec. Hence, the impulsive gamma ray limit set with the CsI detector is a factor of two larger than the expected flux from the 2 September 1966 flare. This can be compared with the neutron limit which was one fifth that expected from the same flare. However, the production of neutral pions is very dependent on the SEP's characteristic rigidity. If this flare had had a $P_o$ of 100 MV instead of 60 MV, then the expected gamma ray flux would be near 1/cm$^2$ sec. Therefore, it would seem profitable to continue the search for these high energy gamma rays with a detector similar to but larger than the one used in this experiment.
2. Summary

The search for solar neutrons described in this thesis has resulted in the assignment of new lower limits on the solar neutron flux. These limits were set for the continuous flux at a time near the solar maximum. Limits were also set for the impulsive flux associated with several small solar flares. The limits that have been set have also shown that the simple detection scheme described in this thesis can be an effective one in the search for solar neutrons.

It is clear from the results discussed in this paper that several of the detection schemes presently available have the capabilities of testing the predictions of L & R for large solar flares. It is probably equally clear, however, that dramatic improvements in detectors will be necessary to measure the emission of neutrons from the quiet sun. It is not clear at this time how these improvements will come about. Zych's (1968) results show that the directional neutron detectors now envisioned will be troubled by the energetic protons produced in carbon.

Because of their importance in the understanding of solar flare events, efforts to measure these neutral solar radiations should continue. This will be especially important during the present solar maximum. These measurements can probably best be done on a satellite because of the almost complete time coverage it would allow. However, other methods can and should also be used.
One experiment not yet suggested would use the present type of detector on a solar probe, approaching the sun to a distance of ≈ 0.5 A.U. This method would significantly reduce the loss of solar neutrons due to decay and hence allow observation of a lower quiet sun flux. It would also provide good time coverage for solar flare event neutrons. However, it may be troubled, as all satellite experiments seem to be, by the prompt arrival of the charged SEP's. Hence, charged particle rates would also have to be monitored.

If the search must use balloon borne detectors the author suggests a complete solar monitor package. This package should include a gamma ray detector (s) sensitive in the energy range 0.3 to 100 MeV, as well as a neutron detector. The neutron detector could be of the same type used here. However, as will be explained in Appendix A, the background counting rate contributed by the atmospheric gamma rays appears to be considerably higher than was originally thought. Pulse shape discrimination to remove the gamma ray effects would result in a worthwhile reduction in the background counting rates and hence in the smallest solar neutron flux that could be observed. Several of these monitor packages could be made up and placed on standby. These would then be launched on several days in succession when there is a large and active region on the sun. This would probably be the best way to observe a solar flare event, and if one is seen, measurements of both the neutrons and gamma rays would be made.
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APPENDIX A

HIGH ENERGY COSMIC RAY ATMOSPHERIC NEUTRONS AND GAMMA RAYS

1. Introduction

In this appendix, we would like to interpret the total background counting rates of the two detectors. In the main section of this thesis the absolute value of this background was not of major importance. What was of interest there were the variations in the background rates so that a differential increase due to solar radiation could be searched for. However, an understanding of the neutral radiation near the top of the atmosphere is also of general interest. Hence, even though this experiment was not designed primarily with this purpose in mind, an attempt is made here to "unfold" the counting rates, and hence to find the intensity and spectral shape of these neutral components.

To do this unfolding it is first necessary to assume that the only two important neutral components are neutrons and gamma rays. Earlier experiments (St. Onge, 1968; and Haymes, 1964, 1964) as well as an inspection of reasonable fluxes and cross sections indicate that this is a very good approximation. In addition, it is necessary to consider the local production of these neutrals in the experimental apparatus. Recently Chupp et al. (1968) measured the gamma ray production at balloon altitudes in large paraffin
blocks which surrounded a central gamma ray detector. This was done by comparing the pulse height spectrums obtained before and after the paraffin was dropped away from the detector. They found that there was very little difference in these two cases except for the 2.2 MeV deuteron formation line due to low energy neutron absorption in the hydrogen of the paraffin. This indicates that the net continuous gamma ray production, at least in low Z materials, is very small and can be neglected. Low Z material makes up better than 90% of the present experimental package weight. Because the situation is expected to be similar, and for lack of better information, it was assumed that the local production of high energy neutrons is probably also small. At any rate any locally produced neutrals will be taken care of in the ±20% errors that will be assigned to the results of this appendix.

The plastic detector is sensitive to neutrons between 7 and -100 MeV. This is an energy region in which there is great interest and very few measurements (Haymes, 1965). These neutrons are important because they may be the main source of energetic protons (through neutron decay) in the inner trapping zone. Hess and Killeen (1966) and Dragt et al. (1966) have independently calculated the strength of this source that is required to balance the loss of protons in the zone by atmospheric ionization losses. Both found that if their atmospheric model is correct, the theoretical atmospheric albedo neutron leakage flux calculated
by Lingenfelter (1963) is too low by a factor of 10 to 50 to supply the inner zone protons. However, they stress the importance of better measurements of the high energy atmospheric neutron flux. There is also interest in this energy range to help in the design of second generation solar neutron detectors.

The plastic detector is also sensitive to gamma rays between 3 and ~20 MeV. The present CsI (2" x 2") detector is sensitive to higher energy gamma rays, between 10 and ~70 MeV. The CsI (2" x 2") detector, unlike the plastic detector, can be considered neutron insensitive. The main interest in these energetic gamma rays is in the understanding of the build-up of the radiation in the atmosphere and also to help in the design of detectors to do gamma ray astronomy.

2. Experimental Results

In this section we will briefly review the experimental results of the present experiment. We will also discuss the results from two other experiments (Chupp et al., 1968; and Peterson et al., 1966) that will be used in the determination of the atmospheric gamma ray spectrum. The main necessity for recalling the other two experiments is because of the small gamma ray energy overlap of the present two detectors.

The depth dependence of all the counting rates between 200 and 650 g/cm² of atmosphere was well fitted by
an equation of the form \( R(x) = C \exp(-x/X_0) \). Here \( R(x) \) is the counting rate at an atmospheric depth of \( x \text{ g/cm}^2 \) and \( X_0 \) is a characteristic absorption length. Near the top of the atmosphere (i.e., \( x < 20 \text{ g/cm}^2 \)) the best form was \( R(x) = A(1 + bx) \). Note that in this linear approximation, \( A \) is the counting rate at the top of the atmosphere. The counting rates given by \( A \) will be the ones used in this appendix. Hence, the fluxes determined will be those at the top of the atmosphere. For convenience, the depth coefficients are reshown here in Table A-1.

### TABLE A-1

**DEPTH COEFFICIENTS**

P and CsI correspond to the plastic and CsI detectors, CPS-charged particle shields, and D#1 etc. - discriminator bias level number 1

<table>
<thead>
<tr>
<th>Detector</th>
<th>( X_0 \text{(g/cm}^2) )</th>
<th>( A \text{(cts/sec)} )</th>
<th>( b \text{(cm}^2\text{/g)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-CPS</td>
<td>168 ± 4</td>
<td>1334 ± 11</td>
<td>0.036 ± 0.001</td>
</tr>
<tr>
<td>CsI-CPS</td>
<td>157 ± 5</td>
<td>320 ± 5</td>
<td>0.033 ± 0.002</td>
</tr>
<tr>
<td>P-D#1</td>
<td>168 ± 5</td>
<td>38.4 ± 1.1</td>
<td>0.057 ± 0.022</td>
</tr>
<tr>
<td>P-D#2</td>
<td>170 ± 4</td>
<td>16.6 ± 0.5</td>
<td>0.053 ± 0.003</td>
</tr>
<tr>
<td>P-D#3</td>
<td>172 ± 5</td>
<td>11.3 ± 0.3</td>
<td>0.053 ± 0.003</td>
</tr>
<tr>
<td>CsI-D#1</td>
<td>148 ± 9</td>
<td>4.34 ± 0.15</td>
<td>0.070 ± 0.003</td>
</tr>
<tr>
<td>CsI-D#2</td>
<td>148 ± 5</td>
<td>1.76 ± 0.07</td>
<td>0.077 ± 0.004</td>
</tr>
<tr>
<td>CsI-D#3</td>
<td>153 ± 5</td>
<td>0.82 ± 0.04</td>
<td>0.076 ± 0.004</td>
</tr>
<tr>
<td>CsI(3&quot;x3&quot;)</td>
<td>170 ± 4</td>
<td>-----</td>
<td>0.055 ± 0.004</td>
</tr>
</tbody>
</table>
Also shown in Table A-1 are the same atmospheric depth coefficients for an earlier gamma ray experiment (Chupp et al., 1968). This experiment used a 3" x 3" CsI detector [called CsI (3" x 3") from here on] to search for the presence of 2.2 MeV gamma rays from the sun. It was flown from the same location and at approximately the same time (Flight 314-P, June 1967) as the present series of flights. The coefficients shown in Table A-1 were taken from the pulse height spectrum near 2.2 MeV. However, the lack of evidence for a line in the spectrum indicated that the intensity of the 2.2 MeV line in the atmosphere must be less than 1/10 the intensity of the continuous gamma ray flux in the energy region 2.2 ± 0.1 MeV. Hence these coefficients are representative of the same continuous gamma ray spectrum as was seen by the present plastic detector.

Comparison of the depth coefficients listed in Table A-1 is informative. However, it should be noted that these coefficients are dependent on latitude and on the time of the solar cycle. Hence, only detectors that are launched from the same location and at nearly the same time can be directly compared. All those in Table A-1 satisfy these requirements.

It was first thought that the different depth coefficients of the present CsI (2" x 2") and plastic detectors implied that, in the main, these two detectors were counting different types of radiation. However, the CsI (3" x 3") has the same depth coefficients as the plastic detector, and
it is counting gamma rays in the same energy range as the plastic detector. Because CsI detectors are relatively insensitive to neutrons, this suggests that all three detectors are counting mainly gamma rays. The higher gamma ray threshold of the present CsI (2" x 2") detector may account for its different depth coefficients. Hence, some other experimental data must be used to determine the gamma ray intensity and spectral shape in the 1 to 15 MeV range.

Fortunately, Peterson et al. (1966) have performed the type of experiment that is required. This experiment used a 3" x 3" NaI detector [called NaI (3" x 3") from here on], and it was also flown from the NCAR balloon base in Texas in February 1966. This detector covered the gamma ray energy range from 1 to 11 MeV. Their differential pulse height spectrum taken at 3.6 g/cm² was corrected by us to the top of the atmosphere with the coefficients from the CsI (3" x 3") detector shown in Table A-1. A 9% correction was also made for the small change in the solar cycle. This latter correction was obtained by comparison of the counting rates near 2.2 MeV from the NaI (3" x 3") and the CsI (3" x 3") detectors. The resultant pulse height spectrum is shown as the solid stepped histogram in Figure A-1 and it is well fitted by the equation:

\[ N(E_e) = 0.48E_e^{-1.35} \text{ (counts/cm}^2\text{ sec MeV).} \]

Note that this is not a gamma ray flux. It represents the differential electron energy loss spectrum in a 3" x 3" NaI
scintillator that is at the top of the atmosphere above Texas at a time near July-December 1967. By assuming that the energy loss spectrum is produced solely by the atmospheric gamma rays, a gamma ray spectrum may be unfolded.

3. Interpretation of Results

Before we talk about the specific spectrum unfolding procedures, it is informative to discuss the general problem of the transformation of counting rates into fluxes. There are two types of fluxes that are of general interest, the flux from a point source and the flux from an extended source. The radiation from a distant point source, because it is a plane wave at the detector, can be described by the flux \( J_p = \text{(particles/cm}^2 \text{sec)} \). This gives the number of particles passing through a unit area normal to the incident radiation per unit time. However, the radiation from an extended source is best described in terms of the differential unidirectional flux, \( j_o(\theta \phi) = \text{(particles/cm}^2 \text{sec sr)} \). This unit describes the number of particles passing through a unit area normal to the direction defined by \( \theta \) and \( \phi \), per unit time per unit solid angle around the direction defined by \( \theta \) and \( \phi \).

Now, in general, the counting rate of a detector is directly proportional to the flux incident on the detector. The proportionality constant is a term we call the detector sensitivity (or response function). The sensitivity is normally the product of the detector's area, in a given
direction, times its efficiency in that direction. It is in general also a function of $\theta$ and $\phi$. However, for gamma rays and neutrons, the sensitivity is given by $S(\theta \phi) = A(\theta \phi) [1 - \exp(-\lambda L(\theta \phi))]$, where $A(\theta \phi)$ is the area of the detector normal to the direction defined by $\theta$ and $\phi$, $L(\theta \phi)$ is its length along the same direction, and $\lambda$ is the absorption coefficient of the radiation in the detector. Now if, as in most cases, the product $\lambda L(\theta \phi) \ll 1$, then the above equation can be expanded to give $S(\theta \phi) = A(\theta \phi) L(\theta \phi)\lambda$. But $A(\theta \phi) L(\theta \phi)$ is just the volume of the detector for any $\theta$ and $\phi$, and hence the sensitivity $S$ is effectively isotropic or independent of $\theta$ and $\phi$. This has been experimentally shown to be true for a large variety of cases.

We have shown in the main section of this thesis, Section II, that the neutron sensitivity of the plastic detector and the gamma ray sensitivity of the CsI detector is in fact nearly isotropic for the above reasons. The gamma ray sensitivity of the plastic detector is not quite isotropic because of the long range of the secondary electrons and the fact that the detector's length is twice its diameter. However, since there is no knowledge of the angular dependence of the atmospheric gamma rays in this energy range, we have averaged the gamma ray sensitivity of the plastic detector over all directions as

$$ \overline{S} = (4\pi)^{-1} \int_{4\pi} S(\theta \phi) d\Omega $$
Hence, introducing the energy dependence, the counting rate from a point source, such as the sun, is given by:

\[
R_{\text{cts/sec}} = \int_{E_{\text{min}}}^{E_{\text{max}}} S(E) \frac{dJ_p(E)}{dE} dE
\]  

where \( S(E) \) is the energy dependent isotropic sensitivity \((\text{cm}^2)\) and \( \frac{dJ_p(E)}{dE} \) is the energy dependent differential flux from the point source \((\text{particles/cm}^2 \text{ sec MeV})\). On the other hand, the counting rate from an extended source, such as that produced in the atmosphere, is given by:

\[
R_{\text{cts/sec}} = \int_{E_{\text{min}}}^{E_{\text{max}}} \int S(E, \theta, \phi) \left[ \frac{d^2j_o(E, \theta, \phi)}{dE d\Omega} \right] dE d\Omega
\]

where \( \frac{d^2j_o(E, \theta, \phi)}{dE d\Omega} \) is the energy and angular dependent differential flux from the extended source \((\text{particles/cm}^2 \text{ sec MeV sr})\). However, if the sensitivity is not a function of angle we can integrate over the solid angle and define the integrated directional flux:

\[
\frac{dJ_o(E)}{dE} = \int_{4\pi} d^2j_o(e, \theta, \phi) d\Omega
\]

and then the counting rate is given by:

\[
R_{\text{cts/sec}} = \int_{E_{\text{min}}}^{E_{\text{max}}} S(E) \frac{dJ_o(E)}{dE} dE
\]
Note that if the detector sensitivity is isotropic, it is not necessary to assume that the flux is isotropic. At any rate, it is this integrated directional flux that will be given for the atmospheric flux. Because the measurements are made at the top of the atmospheric, and if it is assumed that there are no extra-terrestrial sources, then the equivalent isotropic directional flux ($j_0'$) will be $j_0' = (2\pi)^{-1}J_0$. However, any other directional dependence can be assumed as long as the integral over solid angle equals $J_0$.

As we have seen above, the basic equation for unfolding the extended atmospheric gamma ray or neutron flux is Equation A-2. However, when a pulse height spectrum is given, as with the 3" x 3" NaI detector, it is more convenient to treat Equation A-2 as a matrix equation. Then Equation A-2 becomes:

$$C(E_i) = R(E_i, E_j) \times N(E_j).$$  \hspace{1cm} A-3

Here $C(E_i)$ is a nx1 column vector where each element is the counting rate in an energy bin around $E_i$. The gamma ray flux is also a mx1 column vector, $N(E_j)$, where each element gives the number of photons/cm$^2$ sec in an energy bin around $E_j$. These two are related through the nxm matrix $R(E_i, E_j)$, where each element gives the sensitivity of the detector for the energy bin $E_i$ to a unit gamma ray flux of energy $E_j$. It is often called a response matrix. Note that because $E_i$ must be less than $E_j$, all the elements below the diagonal
must be zero.

Because the atmospheric gamma ray spectrum in the energy region 1 to 11 MeV is continuous (i.e., no line structure in the pulse height spectrum), the response matrix can be a smoothed one. That is, only the larger spectral features such as the full energy peak, the 1st and 2nd escape peaks and the Compton continuum will be included. These features were treated as if they were rectangular. These simplifying features have been used before (Young and Burrus, 1968) and they are perfectly satisfactory for a spectrum with few or no gamma ray lines.

The response matrix we used was a 12 x 15 matrix, where the energy bins were 0.5 MeV wide for the energies between 1 and 3 MeV and 1 MeV wide above that. The individual elements were derived from the information compiled by Heath (1964). This author has gathered together the very considerable amount of information needed to construct a very precise response matrix for a 3" x 3" NaI detector. In particular he gives the total detection efficiency up to 10 MeV as well as the photo-fraction efficiencies up to 3 MeV for this size detector. The photofraction gives the fraction of the total interactions in the detector that land in the full energy peak.

The present response matrix was constructed as follows: Below 3 MeV, the photofraction portion of the full sensitivity is assigned to the 0.5 MeV wide bin that is at the same energy as the gamma ray (i.e., the full
energy bin). The rest of the total sensitivity is assigned equally to all energies below the minimum energy of the full energy bin. For example, the fourth energy bin covers 2.5 to 3.0 MeV. The total sensitivity of a 3" x 3" NaI detector for a 2.75 MeV gamma ray is 28 cm$^2$ and the photofraction is 31.5%. Hence we assigned a sensitivity of $28 \times 0.315 = 8.8$ cm$^2$ to the fourth bin and a sensitivity of $(1 - 0.315) \times 28/5 = 3.8$ cm$^2$ to the three lower bins.

Above 3 MeV pair production begins to become important in NaI. The energy loss in the NaI detector from a pair interaction will fall into the full energy peak or the 1st and 2nd escape peaks. The latter two peaks correspond to the escape of one or both of the 0.51 MeV gamma rays associated with the pair positron decay, escaping from the detector. Hence, all of the pair response fall within a one MeV wide bin. The effective range of a 15 MeV electron in NaI is less than 1 cm, so that edge effects can be neglected. Therefore, the one MeV wide full energy bins above 3 MeV include photofractions from successive Compton interactions in the detector, obtained by extrapolating the curves given in Heath (1964), and all of the sensitivity that is contributed by pair production. The complete derived response matrix is shown in Table A-2.

To use this response matrix the atmospheric gamma ray vector energy bins were assigned values by assuming a flux dependence of the form $dJ(E_{\gamma})/dE_{\gamma} = A E_{\gamma}^{-n}$. The terms $A$ and $n$ were then varied to obtain a best fit to the data
TABLE A-2

THE DERIVED RESPONSE MATRIX FOR A 3" x 3" NaI DETECTOR FOR GAMMA RAYS BETWEEN 1 - 11 MeV

| C_1 (1-1.5) | 11.5 | 11.5 |
| C_2 (1.5-2) | 7.0  | 4.0  |
| C_3 (2-2.5) | 5.0  | 5.0  |
| C_4 (2.5-3) | 3.8  | 3.8  |
| C_5 (3-4)   | 2.8  | 2.8  |
| C_6 (4-5)   | 1.9  | 1.9  |
| C_7 (5-6)   | 1.3  | 1.3  |
| C_8 (6-7)   | 1.0  | 1.0  |
| C_9 (7-8)   | 0.7  | 0.7  |
| C_10 (8-9)  | 0.5  | 0.5  |
| C_11 (9-10) | 0.4  | 0.4  |
| C_12 (10-11)| 0.2  | 0.2  |

| N_1 (1-1.5) | 5.0  |
| N_2 (1.5-2) | 3.8  |
| N_3 (2-2.5) | 2.8  |
| N_4 (2.5-3) | 1.9  |
| N_5 (3-4)   | 1.3  |
| N_6 (4-5)   | 1.0  |
| N_7 (5-6)   | 0.7  |
| N_8 (6-7)   | 0.5  |
| N_9 (7-8)   | 0.4  |
| N_10 (8-9)  | 0.2  |
| N_11 (9-10) | 0.2  |
| N_12 (10-11)| 0.2  |
| N_13 (11-12)| 0.2  |
| N_14 (12-13)| 0.2  |
| N_15 (13-14)| 0.2  |
from the NaI (3" x 3") detector. The results of this are shown in Figure A-1. The solid stepped curve is Peterson et al.'s (1966) corrected pulse height distribution. The dashed and dotted straight lines are the assumed gamma ray spectrums and the corresponding dashed and dotted stepped curves are the resultant pulse height distributions calculated from these. Hence, if we can assume the pulse height spectrum given by Peterson et al. (1966) is due mainly to atmospheric gamma rays interacting in the detector, then this atmospheric gamma ray flux is well represented by

\[ \frac{dF}{dE_\gamma} = (1.0 \pm 0.2)E_{\gamma}^{-1.3} \pm 0.2 \text{ (photons/cm}^2 \text{ sec MeV)} \]

in the energy range 2 to 12 MeV. The errors shown were estimated from the fitting accuracy and errors in the response matrix. This flux is shown in Figure A-3 and is labeled NaI (3" x 3").

The counting rates of both the present CsI (2" x 2") and plastic detectors will now be unfolded. In all of the following discussions, the unfolding will be done using a numerical integration of Equation A-2, and the energy spectrum of both the gamma ray and the neutron fluxes will be taken to be power laws. Hence, the counting rate of the ith discriminate \( R_i \) will be given by

\[ R_i = \int_0^\infty S_i(E) AE^{-n} dE = \sum_j S_j(E_j) AE_j^{-n} \Delta E_j \quad \text{A-4} \]
Figure A-1

Assumed atmospheric differential gamma ray spectrums and their resultant pulse height distributions in a 3" x 3" NaI scintillator. The heavy solid stepped function is an experimentally determined pulse height distribution in a 3" x 3" NaI (Peterson et al., 1966). The light solid line shows the flux $1.2 \frac{E^{-1.5}}{\gamma}$ (photons/cm$^2$ sec MeV) and the light solid histogram shows the pulse height distribution it would produce in a 3" x 3" NaI scintillator. Similarly, the dashed line and histogram corresponds to a flux of $1.0 \frac{E^{-1.3}}{\gamma}$ (photons/cm$^2$ sec MeV) and the dashed and dotted line and histogram to a flux of $0.8 \frac{E^{-1.1}}{\gamma}$ (photons/cm$^2$ sec MeV).
Figure A-1
The best fit to the observed counting rates from the three discrimination levels of each detector is accomplished by first estimating a power index $n$. The calculations of Equation A-4 are then carried out using the sensitivities given in the main part of this thesis. The term $A$ is calculated by a least square fit and then $\delta R(n)$ is determined where

$$\delta R(n) = \left[ \frac{1}{\sum_{i=1}^{3} |R_{obs} - R_i(n)|} \right]^{1/2}$$

Another $n$ is picked and the whole thing repeated until a minimum $\delta R(n)$ is found. The flux using this $n$ gives the best fit to the experimental data. Using this approach, some worst case fluxes were found.

Let us first assume that the plastic detector is not counting any gamma rays, and then find the neutron flux required to account for the observed counting rates. Using the observed counting rates for the discrimination levels $P-D\#1, 2, 3$ of 38.4, 16.6, and 11.3 cts/sec, and the response functions shown in Figure II-7 and Equation A-4 above, we find an atmospheric neutron flux of

$$dN(E_n)/dE_n = 0.44 E_n^{-1} \text{ (neutrons/cm}^2 \text{ sec MeV).}$$

This is a very large flux compared to other measurements. It is listed as Forrest (No Gamma) in Figure A-2. The other curves in this figure will be discussed later.

Similarly, we can make the assumption that the plastic detector is not counting any neutrons and find the gamma ray flux required to account for the observed counting
rates. Again using the observed counting rates, the plastic detector gamma ray response functions given in Figure II-9 and Equation A-4 above, we find an atmospheric gamma ray flux of $dN(E_\gamma)/dE = 0.24 E^{-0.7}$ (photons/cm$^2$ sec MeV) in the energy range 3 to 20 MeV. Although the intensity of this flux is reasonable, its shape is inconsistent with the spectral shape derived from Peterson et al. (1966) data [NaI (3" x 3")]. This spectrum is shown on Figure A-3 and is labeled Forrest (Plastic-No Neutron).

Finally, we can make the assumption that the present CsI detector's counting rates are entirely accounted for by the atmospheric gamma rays. This is a better approximation than the above two in that it was shown in the main part of this thesis that there is experimental evidence that the neutron sensitivity in CsI is nearly a factor of ten smaller than its gamma ray sensitivity. At any rate, using the observed counting rates in the CsI detector of 4.34, 1.76, and 0.82 cts/sec, and the gamma ray sensitivity shown in Figure II-11 and Equation A-4 above, we determine a gamma ray flux of $dN(E_\gamma)/dE_\gamma = (12 \pm 3) E^{-2.3 \pm 0.1}$ (photons/cm$^2$ sec MeV) in the energy range 10 to 60 MeV. This curve is also shown on Figure A-3 and is labeled Forrest (CsI).

The other curves shown in Figure A-2 are as follows: In 1963, Sydor (1964) made several balloon flights with a directional neutron detector. He found that the neutron flux at 8.6 g/cm$^2$, when integrated over all angles, was $dN/dE_n = 1.8 E_n^{-1.3}$ neutrons/cm$^2$ sec MeV in the energy range
Figure A-2. Atmospheric albedo differential neutron flux. See text for discussion and references.
Figure A-3. Atmospheric differential gamma ray flux. See text for discussion and references.
30 to 130 MeV. This flux was corrected to 0 g/cm$^2$ by dividing by 1.47 (i.e. = 1 + 8.6 $\times$ 0.055) and to the present portion of the solar cycle by dividing by 1.21 (obtained from the data in Table 1 in Lingenfelter, 1963). This yielded a flux of 1.0 $E_n^{1.3}$ neutrons/cm$^2$ sec MeV, and it is labeled Sydor in Figure A-2. Another measurement made in 1963 by Haymes (1964) with an omni-directional detector found the flux in the 1 to 10 MeV region and at the top of the atmosphere over Texas to be $\frac{dN}{dE_n} = 0.073 E_n^{1.3}$ neutrons/cm$^2$ sec MeV. This result was also corrected for solar cycle changes by the factor 1.21 and is labeled Haymes. The curve marked Lingenfelter was taken directly from Figure 3 in Lingenfelter (1963) and gives his calculated cosmic-ray neutron leakage flux for the correct geomagnetic latitude (i.e., 40°) and solar cycle time. The curve marked Zych was derived from a recent measurement with a neutron spark chamber that was also performed over Texas. Zych and Frye (1968) estimated that the neutron albedo in the energy range 20 to 100 MeV was 0.11 neutrons/cm$^2$ sec. Because they did not give any spectral dependence, we have transformed this into a flat differential flux by dividing by a $\Delta E_n = 80$ MeV. This result is marked Zych in Figure A-2. There has been another very recent attempt by St. Onge (1968) to measure the atmospheric neutron flux over Texas with an omnidirectional detector. Unfortunately, instrumental failure prevented him from getting spectral information above 100 g/cm$^2$ of atmosphere. To take his
data to the top of the atmosphere, the results in St. Onge's (1968) Figure 34 were divided by 3.9 and are marked St. Onge in Figure A-2. The correction factor was taken from the data of the present plastic detector (See Figure III-3 in the main part of this thesis), but it should be remembered that the present plastic detector was counting both neutrons and gamma rays, and hence, the factor 3.9 may not be exactly correct for St. Onge's (1968) neutron data. Finally, we show the neutron flux derived by Freden and White (1962). This flux is based on the observed intensity and spectral shape of the trapped protons in the inner zone. They suggest that the minimum in the atmospheric neutron spectrum may be caused by an increase in the non-elastic cross section of the atmospheric nitrogen and oxygen near 20 MeV.

In relation to the present results, the curves shown in Figures A-2 and A-3 indicate at least two things: First, except for those marked Sydor, the neutron flux derived from the present plastic detector, assuming no gamma rays, is at least a factor of 10 higher than any of the others. On the other hand, the gamma ray flux derived from the same detector, assuming no neutrons, is in rough agreement with the flux derived from the results of the NaI (3" x 3") detector. From this we can conclude that most of the counting rate in the present plastic detector is due to gamma ray interactions. However, because of the rapid fall-off of gamma ray sensitivity with increasing energy, the gamma ray spectral shape required by the present plastic
detector is much flatter than that obtained with the NaI (3" x 3") detector. Hence, it appears necessary to require that there be some counting rate produced by neutrons in the plastic detector, particularly in the higher discriminator levels. Although the errors are too large to define the required neutron flux with any certainty, the results in Table A-3 show a reasonable solution. The first column in Table A-3 shows the counting rates for the three plastic detector discriminator levels, assuming the gamma ray flux found with the NaI (3" x 3") detector (i.e., \( \frac{dN}{dE_\gamma} = (1.0 \pm 0.2) \, E_\gamma^{-1.3} \pm 0.2 \) photons/cm\(^2\) sec MeV). The second column shows the counting rates that would be produced by a neutron flux such as that marked Zych in Figure A-2 (i.e., \( \frac{dN}{dE_n} = 1.4 \times 10^{-3} \) neutron/cm\(^2\) sec MeV). When these two calculated rates are summed together (as shown in the column marked total), it can be seen that within the errors given they do compare with the observed rates.

**TABLE A-3**

**PLASTIC DETECTOR COUNTING RATES**

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gamma ray</td>
<td>neutron</td>
</tr>
<tr>
<td>P-D#1</td>
<td>41 ± 8/sec</td>
<td>4 ± 2/sec</td>
</tr>
<tr>
<td>P-D#2</td>
<td>12 ± 2</td>
<td>2.5 ± 1</td>
</tr>
<tr>
<td>P-D#3</td>
<td>6.6 ± 1.3</td>
<td>2 ± 1</td>
</tr>
</tbody>
</table>
4. Conclusions

Most of the counting rate of the present plastic detector can be accounted for by the gamma ray flux determined from the results of Peterson et al. (1966) with a 3" x 3" NaI detector. This gamma ray flux was: \( \frac{dN}{dE} = (1.0 \pm 0.2) E^{-1.3 \pm 0.2} \) photons/cm\(^2\) sec MeV in the energy 1-10 MeV and is the flux at the top of the atmosphere over Texas in 1967. However, in order to satisfy the counting rates of the higher discriminator levels in the plastic detector, it is necessary to assume the presence of a rather flat or increasing neutron spectrum in the energy region above 20 MeV. A flux of intensity 0.11 neutrons/cm\(^2\) sec in the energy range 20-100 MeV has recently been reported by Zych and Frye (1968) and this flux was found to be sufficient to explain the needed counting rates. Note that this neutron flux is at least a factor of ten higher than that calculated by Lingenfelter (1963). Calculations by Dragt et al. (1966) and Hess and Killeen (1966) have indicated that an energetic cosmic ray neutron albedo flux of the size predicted by both this work and by Zych and Frye (1968) would be sufficient to be a source for the protons in the inner trapping zone.

The gamma ray spectrum above 10 MeV, derived from the results of the present 2" x 2" CsI detector is:
\( \frac{dN}{dE} = (12 \pm 3) E^{-2.3} \) photons/cm\(^2\) sec MeV. This result indicates that there must be a change in the gamma ray spectral shape near 10 to 15 MeV. This may not be unexpected,
in that the gamma ray interaction in the atmosphere changes from pair to Compton in this energy region.
BIBLIOGRAPHY


APPENDIX B

RESULTS OF AN EXPERIMENTAL SEARCH FOR
SOLAR NEUTRONS WITH A DIRECTIONAL NEUTRON DETECTOR

1. Introduction and
Description of the Experimental Apparatus

A new type of directional neutron detector was flown at balloon altitudes in a search for solar neutrons. An unexpected high background counting rate was observed. The origin of this background is not presently known with certainty. However, it is felt that high response to $^{12}$C$(n,3\alpha)$ reactions are the probable cause since the detector has no directional response to these reactions. No effects that could be contributed to solar neutrons were observed. The lowest upper limit solar neutron flux was set at $10^{-2}$ neutrons/cm$^2$ sec MeV in the 10 to 70 MeV range.

The directional neutron detector (Chupp and Forrest, 1966) consisted of 1000 plastic scintillator (NE103) filaments, 1 mm in diameter and 7 cm long. These filaments were potted in a parallel array with a transparent silicon epoxy. The distance between filament axes is 3 mm and the complete detector is a cylinder 4 3/4" diameter x 3 1/2" high. The operation of the detector is based on the fact that the energetic protons from the $n(H^1,p)n^+$ reaction are emitted in the forward direction. Hence, energetic protons pro-
duced by neutrons that are traveling parallel to the filament axis can travel its full range in the scintillator. Neutrons which are traveling perpendicular to the filament axis will produce protons that can travel only a short distance in the scintillator (i.e., its diameter). Therefore, most of the counts above a certain threshold will come from neutrons which are traveling parallel to the filament axis. The detector is directional in the energy range 10 MeV ≤ E_n ≤ 70 MeV. At 15 MeV the efficiency is ~ 2% and the angular response FWHM is 60°. Calculations (Forrest, 1967) indicate that the directional efficiency of the detector above some threshold energy B for neutrons of energy E_n > B is:

\[ \varepsilon(B, E_n) \leq \frac{1}{E_n} \left[ 1 - \left( \frac{B}{E_n} \right)^3 \right] \]

The experimental apparatus consisted of two such detectors, each completely covered by a charged particle shield. One of the detectors had its sensitive axis pointing vertical and the other 45° from the vertical. A motorized line twister rotated the entire experimental package at ~ 1 revolution per eight minutes. A compass and clock photographed every 1.5 minutes determining the pointing direction in time.

The detectors were placed in 30" diameter fiberglass pressure spheres. The spheres together with the styrofoam insulation consisted of ~ 1 g/cm² of material.
outside of the charged particle shields. The detector-sphere weighed ~50 lbs and it was separated from the ~200 lbs of electronics, batteries, and ballast by six foot booms. The 200 lbs mass was always 90° from the detector sensitive axes.

The low counting rate allowed one 32 channel pulse-height analyzer (Ewald and Sarkady, 1965) to be placed on call for the two detectors. A plus or minus sync pulse determined from which of the two detectors the event originated. Figure B-1 shows the output of the FM subcarrier discriminators for two typical events. Events in the two charged particle shields were also monitored. A block diagram of the electronics is shown in Figure B-2.

The FM telemetry was received and the output was recorded, along with a WWV time signal, directly on a wide band video tape recorder. This provided a permanent record of the flight from which data in any time interval could be removed as desired.

2. Physical Details of the Balloon Flight

The balloon was launched from the NCAR Scientific Balloon Flight Station in Palestine, Texas, on 5 August 1966. In local times (CST) the pertinent events were:

- launch at 8:45
- altitude at 10:30 (127 Kft, 3.9 g/cm²)
- solar noon 12:30
- cutdown at 14:15
Figure B-1. Output in time of the subcarrier discriminators for two typical neutron events.
Figure B-2

Block diagram of the experimental apparatus for the directional neutron detector experiment.
During the flight the balloon drifted nearly directly west and went ~ 240 miles or -4° longitude.

All systems appeared to function properly during the flight. The temperature in the electronics package was monitored until 12:20 CST. The temperature was 26°C at launch, dropped to a minimum of 13°C at 94 Kft, and then rose to 15.5° at altitude.

A post flight checkout was carried out after returning to the University of New Hampshire laboratory. These tests showed all systems were still operating properly and that there were no significant changes compared to the pre-flight check out.

3. Discussion of Results

The charged particle rate versus pressure are shown in Figure B-3. The e-folding length for pressures > 150 mb were ~ 170 mb. The charged particle box (13" x 7 5/8" x 7 5/8") has an isotropic projected area $G = \frac{A}{4} = 809 \text{ cm}^2$. Using this, the computed flux was $2.78 \pm 0.04/\text{cm}^2 \text{ sec}$ for Det. #1 (vertical detector) and $2.38 \pm 0.04/\text{cm}^2 \text{ sec}$ for Det. #2 (45° detector) at ~ 80 mb. At the maximum altitude of 3.5 mb the fluxes were $1.32 \pm 0.01/\text{cm}^2 \text{ sec}$ and $1.17 \pm 0.01 \text{ cm}^2 \text{ sec}$ respectively. The consistent difference in rates at all altitudes could be due to a non-isotropic distribution of the charged particle flux. The charged particle rate remained constant within statistics for the duration of the flight at 3.5 mb. Dead time corrections
Figure B-3. Counting rates vs. atmospheric pressure for the directional neutron detector flight.
due to charged particle events were less than 2%.

Figure B-3 also shows the neutron counting rate versus pressure. The notation \( \sum > 6 \) implies all the counts in channel 6 and above have been summed together. This corresponds to a threshold \( B = 10 \) MeV. The average counting rate at 3.5 mb was 0.150 ± 0.005/sec for Det. #1 and 0.155 ± 0.007/sec for Det. #2. The e-folding length above 150 mb is approximately 180 mb. The pulse height spectrum for ~100 minutes of data at 3.5 mb is shown in Figure B-4. Figure B-5 shows the neutron counting rate for Det. #1 versus the sun's angle from the vertical. Each point represents approximately 10 minutes of data. Det. #2's neutron counting rate in each of four quadrants is shown in Figure B-6. Each of these points represents approximately 25 minutes of data.

4. Interpretation of Results

The main feature of this experiment was the unexpected high neutron detector counting rate above the 10 MeV threshold. Our estimates of the neutron detector background counting rates followed from the below idealized analysis. The counting rate when looking at both the source and the background, \( C(b + s) \), would be:

\[
C(b+s) = F_b G_o \epsilon_{ISO} + F_s A \epsilon_{ISO} + 2F_b A \epsilon_d + F_s A \epsilon_d.
\]

Here, \( F_b \) and \( F_s \) are the fluxes of the isotropic background and the point source respectively. \( G_o \) and \( A \) are the iso-
Figure B-4. Directional neutron detector pulse height spectrums obtained during balloon float.
Neutrons (counts/sec). If solar neutrons were present the counting rate would increase at small angles.

Figure B-5. Neutron detector counting rate vs. the angle between Detector #1 and the sun. If solar neutrons were present the counting rate would increase at small angles.
Figure B-6. Neutron detector counting rate vs. pointing direction. Evidence for solar neutrons would be seen when detector was pointing south.
tropic projected area and the directional end area. $\epsilon_{ISO}$ and $\epsilon_d$ are respectively the isotropic and directional efficiency. The factor of 2 comes from the \( \pi \) symmetry of the detector. Now when looking away from the source, the background rate \( C(b) \) should reduce to

$$C(b) = F_b G_0 \epsilon_{ISO} + F_s A' \epsilon_{ISO} + 2F_b A \epsilon_d,$$

where the projected area to the source is now \( A' \).

Tests with 15 MeV neutrons and other arguments indicated that $\epsilon_{ISO}$ would be very small compared to $\epsilon_d$. (Some of the arguments were the low scintillation efficiency of energetic alpha particles and the long range and low $dE/dX$ of energetic electrons). Hence $C(b+s)$ would reduce to

$$C(b+s) \approx 2 F_b A \epsilon_b + F_s A \epsilon_d,$$

where $F_b$ would consist of albedo and locally produced energetic neutrons. Our estimates of $C(b)$ were made using the albedo neutron spectrum measured by Haymes (1964) in the 1-14 MeV region.

$$\frac{dF_n(E_n)}{dE_n} = \frac{0.12}{4\pi} E_n^{-1.3} \text{ neutron cm}^2 \text{ sec-MeV-Steradian}$$

For our detector

$$A = 8 \text{ cm}^2$$

$$\epsilon(E_n) = 2 \times 10^{-2} \frac{15}{E_n} \text{ for } E_n > B$$

$$\Delta \Omega = \pi \text{ (Steradian)}$$
then the expected background rate due to albedo neutrons would be

\[ C_b(n) = 2\pi A \int_{dE}^\infty \varepsilon(E_n) F_b(E_n) \, dE_n = 6 \times 10^{-3} / \text{sec} \quad B=10\text{MeV} \]

The measured efficiency for 6 MeV gammas producing counts above channel 6 was approximately \(4 \times 10^{-5}\). Using a differential energy spectrum of \(dF_\gamma/dE = 0.9 E_\gamma^{-1.5}\) photons/cm\(^2\) sec MeV based on observations of Frye et al. (1966) and Cline (1961), then

\[ C_b(\gamma) = 8 \int_{6\text{MeV}}^\infty 4 \times 10^{-5} E_\gamma^{-1.5} \, dE_\gamma = 0.3 \times 10^{-3} / \text{sec for } \gamma\text{'s} \]

Calculations were made of the number of locally produced neutrons from charged particle interactions in the pressure sphere. It was found that this should produce a background comparable to \(C_b(n)\). Summing these, a total background of approximately \(1-2 \times 10^{-2}/\text{sec}\) is obtained. The measured background was \(15 \times 10^{-2}/\text{sec}\).

Other effects which could cause an apparent increase in the background rate are telemetry noise, charged particle shield leakage, and gain changes, or malfunctions of the detector during the flight.

During the balloon flight a series of thunderstorms in the area caused considerable noise in the telemetry signal. Noise removal utilized the known polarity, shape, and
time relation of the sync pulse and coded pulse height analyzer signal on the 22 kc and 70 kc subcarrier. These two pulses were displayed simultaneously on a dual trace scope. An operator then visually separated noise events from true events. From 180 minutes of recorded data at altitude, approximately 100 minutes of noise free data was obtained.

The charged particle shield leakage ratio was measured in the laboratory with minimum ionizing μ-mesons. For the worst light collection geometry it was at least $10^{-3}$. If every charged particle which leaked through the shield and entered the neutron detector produced a count, then:

$$C_b(cp) = 10^{-3} \times 1.3 \left( \frac{c.p.}{cm^2 \text{ sec}} \right) \times 10^2(cm^2) = 0.13/\text{sec}$$

where $G_o = 10^2 \text{ cm}^2 = \text{projected area of the neutron detector.}$ However, the largest signal that a minimizing ionizing particle ($dE/dX - 2 \text{ MeV/cm}$) could deposit in the neutron detector is approximately 14 MeV. This would be the case if the particle succeeded in traveling down the full 7 cm length of a 1 mm diameter filament. Only a very small number of particles would fall in the correct solid angle to do this. The maximum signal produced from these particles when traveling perpendicular to the filament axis is approximately 7 MeV. More heavily ionizing particles would have a much higher rejection ratio because of the
larger energy loss in the charged particle shield. One would also expect distortions in the neutron pulse height spectrum at approximately 10 MeV (channel #6) for charged particle leakage of this magnitude. Figure B-4 does not indicate this.

Gain changes and malfunctions during the flight appear unlikely for several reasons. First, the pre and post flight checkouts showed no permanent changes. Also, operation of Detectors #1 and #2 were in a large part independent. Finally, gain changes of the order needed to explain the observed counting rates would most likely be noticeable on the counting rate versus altitude plot. However, no on-board sources were provided for checking the gain during the flight.

The remaining alternatives are (1) the albedo neutron flux at energies > 15 MeV is much higher than extrapolations of measurements in the 1-10 MeV region would indicate and (2) the detector isotropic efficiency for neutrons of energy > 15 MeV is much higher than anticipated. Alternative (1) has some basis in that unpublished measurements of Sydor (1965) with a recoil telescope in the 30-130 MeV range indicate a flux larger than expected. Alternative (2) is also possible through neutron-carbon events in the scintillator. For example, the $^{12}\text{C}(n,n)^{3}\alpha$ cross section is 0.3\(b\) at 20 MeV. This reaction alone could produce the observed counting rate if the response of the detector to this energy $\alpha$'s was high enough. The problem
is that high energy and relatively long range protons can only lose a portion of their energy in the scintillator. Multiple scattering would deflect these protons out of the filaments even if they started out traveling parallel to the filament axis. Energetic $\alpha$ particles, however, because of their very short range, would lose all of their energy in the scintillator filaments. Because of the lack of suitable neutron sources, the detector has only been checked at a single useful energy. This was with 15 MeV neutrons from the $D(T,n)He$ reaction. Tests with neutrons at the Harvard Cyclotron show the detector response to be effectively isotropic at 150 MeV.

Estimates of the solar neutron flux can be carried out with the following analysis. At a 95% confidence level,

\[
C_s = C_{s+b} - C_b \pm 2\sqrt{\frac{C_{b+s}}{T_{b+s}} + \frac{C_b}{T_b}}
\]

where $C_s =$ counts/sec due to solar source
$C_b =$ counts/sec due to background
$T_{b+s}$ and $T_b =$ time interval in which respective measurements were made.

Inspection of Figure 5 and 6 indicate that $C_{b+s} - C_b = 0$. Hence, if $T_{b+s} - T_b$, the maximum counting rate due to a solar source would be:

\[
C_s \leq 2\sqrt{\frac{2C_b}{T}}
\]
A combination of calculations and measurements (Forrest, 1967) indicate an efficiency of \( \varepsilon(E_n) = 15 \times 10^{-2} \times E_n^{-1} \) at a solar-detector axis angle of \( \sim 25^\circ \). Then:

\[
C_s = \int_{10\text{MeV}}^{E_{\text{max}}} F_s (\text{cm}^{-2}\text{sec}^{-1}\text{MeV}^{-1}) A (\text{cm}^2) \varepsilon(E_n) dE_n (\text{MeV})
\]

where \( E_{\text{max}} \) is the proton energy that would give an equal signal when traveling perpendicular to or parallel to the filament axis. \( E_{\text{max}} \) should be approximately \( 70 \pm 20 \text{ MeV} \) for the present detector. With \( E_{\text{max}} = 70 \text{ MeV}, T_b = 2 \times 10^3 \text{ sec}, C_B = 1.5 \times 10^{-1}/\text{sec}, A = 8 \text{ cm}^2, \) and assuming that \( F_s \) is constant, then:

\[
F_s < 2.8 \sqrt{\frac{C_B}{T_b}} \frac{\sqrt{10}}{A \int_{10}^{70} \varepsilon(E_n) dE_n} = 1 \times 10^{-2} \text{ neutrons cm}^{-2}\text{sec MeV}^{-1}
\]

for \( 10 \text{ MeV} < E_n < 70 \text{ MeV} \). This limit is more than an order of magnitude higher than existing solar neutron flux limits (See Figure IV-2).

### 5. Conclusion

A new type of directional neutron detector was flown at balloon altitudes in a search for solar neutrons. An unexpected high neutron background counting rate was observed. The origin of this background is not presently known with certainty. However, it is felt that high response
to $^{12}\text{C}(n,3\alpha)$ reactions are the probable cause. No effects that could be contributed to solar neutrons were observed. The lowest upper limit solar neutron flux was set at $10^{-2}$ neutrons/cm$^2$ sec MeV in the 10 to 70 MeV range.

Further development of this type of neutron detector for cosmic ray experiments would have to lead to provisions for discriminating between events of the type $^{12}\text{C}(n,3\alpha)$ for example, and counting only the elastically scattered protons.
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