Summer 1973

THE FLUX AND ENERGY SPECTRUM OF FAST-NEUTRONS AND GAMMA-RAYS AT BALLOON ALTITUDES

DAVID MICHAEL KLUMPAR

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THE FLUX AND ENERGY SPECTRUM OF
FAST NEUTRONS AND GAMMA RAYS
AT BALLOON ALTITUDES

by

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A THESIS

Submitted to the University of New Hampshire
In Partial Fulfillment of
The Requirements for the Degree of

Doctor of Philosophy
Graduate School
Department of Physics
August, 1972
This thesis has been examined and approved.

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October 3, 1972
ACKNOWLEDGEMENT

The author would like to express his deepest appreciation to Dr. John A. Lockwood for his constant guidance and support throughout all phases of this work. Many hours of long consultation were particularly rewarding.

The author also wishes to thank the many other members of the Physics Department staff, too numerous to mention by name, who contributed so much at various stages while this work was in progress.

Special gratitude is to be extended to my wife, Serene, for her infinite patience and understanding and for laboring through much of the typing of this and earlier drafts.

This research was supported at various phases through grants: NGR30002074 from the National Aeronautics and Space Administration; F19628-68-C-0107 from the U. S. Air Force; and the National Science Foundation under contract number GA33858X.
LIST OF TABLES

1. Summary of Balloon Flights...............................5
2. Number of Events Expected from n-H and n-C Interactions..............................................29
3. Neutron Fluxes and Energy Spectra.......................64
   B-1. Calibration Summary....................................94
   B-2. Neutron Energy and Energy Width Calibration..........95
   B-3. Electron Energy and Energy Width Calibration.......97
ABSTRACT

An organic liquid scintillation detector employing pulse shape discrimination has been used in a series of balloon flights to measure the flux and energy spectrum of fast neutrons ($E > 3$ MeV) and gamma rays ($1 \leq E \leq 10$ MeV) near the top of the atmosphere. The differential neutron leakage spectrum from 3 to 20 MeV at the top of the atmosphere over Palestine, Texas ($\lambda = 42^\circ$N) normalized to solar minimum can be described by a spectrum of the form $0.276 E^{-1.80}$ ($3 \leq E \leq 10$ MeV), $0.035 E^{-0.3}$ ($10 \leq E \leq 15$ MeV), $0.0068 E^{-0.3}$ ($15 \leq E \leq 20$ MeV). The spectrum above 20 MeV inferred from our data may be described by $0.003 E^{0.0}$ ($20 \leq E \leq 50$ MeV) and $6.98 E^{-2.0}$ ($50 \leq E \leq 100$ MeV) neutrons/cm$^2$sec MeV over the indicated energy ranges. The leakage current out of the atmosphere is found to be 0.09 neutrons/cm$^2$sec between 3 and 10 MeV and 0.27 neutrons/cm$^2$sec between 3 and 100 MeV. For a balloon flight from Ft. Churchill, Canada ($\lambda = 68^\circ$N) the 3-20 MeV neutron leakage spectrum extrapolated to the top of the atmosphere and normalized to solar minimum is given by $0.423 E^{-1.65}$ ($3 \leq E \leq 10$ MeV), $0.075 E^{-0.3}$ ($10 \leq E \leq 15$ MeV), $0.015 E^{-0.3}$ ($15 \leq E \leq 20$ MeV) and the inferred spectrum above 20 MeV by $0.006 E^{0.0}$ ($20 \leq E \leq 50$ MeV) and $15.1 E^{-2.0}$ ($50 \leq E \leq 100$ MeV) neutrons/cm$^2$sec MeV over the indicated energy ranges. Integrating we obtain a vertical leakage flux of 0.17 neutrons/cm$^2$sec from 3 to 10 MeV and 0.58 neutrons/cm$^2$sec between 3 and 100 MeV. Implications of this result for the
Cosmic Ray Albedo Neutron Decay Theory (CRAND) are discussed. The atmospheric gamma ray spectrum has been measured between 1 and 10 MeV and is described by a double power law function of the form $0.82 \ E^{-2.2}$ ($1 \leq E \leq 4$ MeV) and $0.36 \ E^{-1.6}$ ($4 \leq E \leq 10$ MeV) photons/cm$^2$sec MeV with a total flux of 0.66 photons/cm$^2$sec at 3.5 g/cm$^2$ during the balloon flight from Palestine, Texas. At 6 g/cm$^2$ over Ft. Churchill, Canada the gamma ray spectrum is described by $1.05 \ E^{-2.2}$ ($1 \leq E \leq 4$ MeV) and $0.4 \ E^{-1.5}$ ($4 \leq E \leq 10$ MeV) photons/cm$^2$sec MeV with a 1 to 10 MeV flux of 0.86 photons/cm$^2$sec.
CHAPTER I

INTRODUCTION

It has long been recognized that neutrons escaping from the Earth's atmosphere where they have been produced by cosmic rays and solar protons could contribute to the particle population of the radiation zones as a result of their spontaneous decay into a proton and an electron. This radiation belt source, known as the Cosmic Ray Albedo Neutron Decay (CRAND) theory was proposed as early as 1958 [Singer, 1958a,b], but the extent of its contribution to the radiation zones has yet to be completely determined. The reason for this lack of complete knowledge as to the relative importance of the neutron leakage flux as a source of radiation zone particles has been succinctly stated in a recent review by Williams [1970]. Of the three unknowns required to solve the problem, only one has been determined. The proton distribution (the result) is well known whereas the source function is unknown. Furthermore, the loss mechanisms which directly determine the trapping lifetimes of these particles are poorly known. This work is directed toward remedying, at least in part, the lack of complete knowledge regarding the source function. The needed source function is completely described when the neutron leakage spectrum above the atmosphere and its angular distribution are known over an energy range of 1 MeV to \(\sim 100\) MeV and as
a function of latitude. Recent reviews of the present state of measurements of neutrons [Haymes, 1965; Lockwood, 1972] have shown that there is still great disparity among the measurements concerning the true energy dependence of the neutron spectrum, especially in the energy range above 10 MeV. The energy range from 10 MeV to 100 MeV is the most important as a source for radiation zone protons and is the least well defined. Differences of a factor of 50 have occurred between various reported results [Preszler, et al., 1972]. A summary of recent measurements and calculations of the neutron leakage spectrum is shown in Figure 1.

A further need for the existence of reliable measurements of the atmospheric gamma ray and the neutron leakage spectrum has arisen only recently with the advent of gamma ray astronomy. Detectors designed to measure the very small flux of cosmic gamma rays from a few hundred keV to ~20 MeV incident on the earth are plagued with background contamination to their data by locally produced and atmospheric gamma rays. Neutron activation in these detectors with the subsequent emission of gamma rays may be a major contributor to such background. Reliable measurements are needed so that these sources can accurately be calculated.

Measurement of the neutron leakage flux and energy spectrum is greatly complicated by the fact that most atmospheric neutron measurements are made with balloon
borne instruments at depths of 3-7 mb. Thus, in order to
determine the true neutron leakage spectrum, some technique
must be used to extrapolate the measurement to the top of
the atmosphere. This extrapolation process is not trivial
and may introduce large errors in the final result. A
further complication with neutron measurements is the con­
tamination of the measurement by neutrons which are pro­
duced locally in the material of the detector and its
associated support equipment. Miscorrection for this
contribution to the data undoubtedly leads to a large
source of error in many of the reported results.

Finally, measurement of the neutron flux is compli­
cated by the large fluxes of gamma rays and charged par­
ticle radiation which also accompany the neutron flux.
Generally speaking, the gamma rays are the most difficult
to exclude in most detectors since they, like neutrons,
are very weakly interacting.

We have used a liquid scintillation proton recoil
spectrometer to measure the neutron spectrum near the top
of the atmosphere. The detector employs a very effective
pulse shape discrimination system to delineate those events
due to neutrons and gamma rays and is completely surrounded
by a plastic anti-coincidence scintillation shield to gate
off those events due to charged particles. The detection
system has been described previously and the reader is
referred to St. Onge and Lockwood [1969a,b], St. Onge [1968]
for further details. We have made five balloon flights
with this detector between 1969 and 1970 at three different vertical cutoff rigidities: 11.3 GV, 4.6 GV, and 0.3 GV. The flight parameters are summarized in Table 1.

In the next chapter is presented a review of the physical processes which contribute to the atmospheric neutron and gamma ray fluxes. Chapter III contains a brief review of the experimental techniques of neutron detection, followed by a description of the detector system and a more detailed treatment of pulse shape discrimination. The mathematical techniques used to unfold the measured data to obtain the true incident spectra are treated in the following chapter. The next three chapters describe the balloon flights, present the data obtained, and discuss these results in terms of other reported measurements. Finally, we conclude by making a set of recommendations for further effort in this field.
TABLE 1: SUMMARY OF BALLOON FLIGHTS.

<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Date</th>
<th>Launch Site</th>
<th>Geomagnetic Latitude(Cut-off Rigidity)</th>
<th>Time of Launch</th>
<th>Time at Float</th>
<th>Float Duration</th>
<th>Float Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>460-P</td>
<td>4/22/69</td>
<td>Palestine, Texas</td>
<td>41°N(4.6GV)</td>
<td>0614CST</td>
<td>0821CST</td>
<td>6hr. 30min.</td>
<td>5.2 mb</td>
</tr>
<tr>
<td>538-P</td>
<td>4/3/70</td>
<td>Palestine, Texas</td>
<td>41°N(4.6GV)</td>
<td>0656CST</td>
<td>0919CST</td>
<td>7hr. 56min.</td>
<td>3.5 mb</td>
</tr>
<tr>
<td></td>
<td>7/5/70</td>
<td>Pt. Churchill, Canada</td>
<td>68°N(0.3GV)</td>
<td>0434CDT</td>
<td>0704CDT</td>
<td>11hr. 57min.</td>
<td>6.0 mb</td>
</tr>
<tr>
<td></td>
<td>10/22/70</td>
<td>Parana, Argentina</td>
<td>21°S(11.3GV)</td>
<td>0607LT</td>
<td>0904LT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11/18/70</td>
<td>Parana, Argentina</td>
<td>21°S(11.3GV)</td>
<td>0514LT</td>
<td>0745LT</td>
<td>10hr. 38min.</td>
<td>4.2 mb</td>
</tr>
</tbody>
</table>
1. Neutron Production in Atmosphere

Neutrons are produced through the interaction of high energy charged particles colliding with some sort of target material. In the earth's atmosphere the high energy charged particles are supplied by the primary and secondary cosmic ray flux continuously striking the earth. The target material in this case is the atmosphere itself, composed mostly of nitrogen and oxygen. At any given point in the atmosphere, a neutron of a prescribed energy may have arrived at that point either by virtue of being produced there, or having propagated there in which case it had been produced at some other point at an earlier time and probably at some higher energy. The problem of determining the neutron distribution in the atmosphere was first treated by Bethe, Korff and Placzek [1940] and has been treated more extensively recently [Lingenfelter, 1963a].

Two basic mechanisms exist for the production of neutrons by nuclear reactions. High energy neutrons $E_n > 10$ MeV are produced by the "knock-on" process where, generally, an energetic cosmic ray nucleon with several GeV or more of energy collides with a target nucleus and a few fast nucleons are ejected immediately in the forward direction. The energies of the "knock-on" nucleons are typically a large
fraction (10-50 percent) of the incident particle energy. As a result of the collision the nucleus may be left in an excited state and after a variable time delay it may break up into a number of particles, including neutrons. This process continues in the nucleonic cascade until the ejected nucleons have enough energy to just enter the next nucleus. This energy is absorbed and the nucleus becomes "heated" and eventually de-excite with the emission of one or more nucleons. This second effect gives rise to what are known as evaporation neutrons which have average energies in the neighborhood of a few MeV. Simpson [1951] has shown that evaporation-type stars produced by cosmic rays having energies of the order of 300 MeV or less accounts for 90% of the cosmic ray neutrons.

Based on these mechanisms Lingenfelter [1963a] has calculated the neutron production distribution in the atmosphere using a diffusion theory approximation to the transport equation. However, he does not treat the neutron distribution above 10 MeV except to determine its probability of contributing to the < 10 MeV distribution as the energetic neutron's energy is degraded by collisions. He also calculates the neutron leakage spectra based on his production calculations [Lingenfelter, 1963b]. In the energy region E > 10 MeV, where the diffusion approximation is no longer valid, the neutron leakage intensities are derived from the experimental spectra of Hess, et al., [1959] as described by Hess, et al. [1961].
Another method of calculating the atmospheric neutron flux from the steady-state neutron transport equation was used by Newkirk [1963]. Instead of the diffusion approximation, which is not accurate near the boundaries of the diffusing medium, Newkirk used a numerical method of solving the transport equation based on difference equation techniques. This technique, known as the $S_n$ method, is based upon transport theory rather than diffusion theory, and is more accurate than the latter in the important region near the top boundary of the atmosphere [Newkirk, 1963].

Since the atmosphere is composed mostly of nitrogen (78.09%) and oxygen (20.98%) with some argon (0.93% by volume), the atmospheric neutron spectrum in the 1-15 MeV region might exhibit structure due to resonances in the total cross sections for nitrogen and oxygen. Such resonance structure in the atmospheric neutron spectrum has recently been predicted by Wilson, Lambiotti and Foelsche [1969]. They used a Monte Carlo transport calculation of fast neutron spectra produced by galactic cosmic ray protons in the atmosphere. In the calculations, fast neutrons are assumed to be produced through an evaporation process after interaction of high energy nucleons with air nuclei. The transport of these evaporation neutrons is dominated by the nuclear resonance structure of the oxygen and the nitrogen in the atmosphere, thus forming depletions in the otherwise smooth evaporation spectrum. They found two pronounced peaks at about 2.5 and 4.9 MeV and apparent points of inflection at about 6.6 and 9 MeV.
2. **Solar Neutrons**

It has been proposed [Biermann, et al., 1951] that neutrons may be produced by nuclear reactions in the sun, particularly during solar flare events, and some fraction of these may be ejected toward the earth. Owing to the short half-life of the neutron (1000 sec. at rest), only a small fraction of the neutrons produced at the sun can possibly reach the earth without decaying. The probabilities of survival are such that the likelihood of observing any solar neutrons in the vicinity if the Earth having energies less than about 50 MeV (survival probability = 20%) in anything but the most intense solar particle events is small. Only neutrons whose kinetic energy exceeds 350 MeV have a survival probability before decay of greater than 50% to travel 1 A.U.

The flux and energy spectrum of solar neutrons to be expected at the earth during major solar flares has been calculated in detail by Lingenfelter and Ramaty [1967] who also reviewed earlier work. Using a model in which solar energetic particles are accelerated above the solar photosphere with some fraction being directed toward the sun and some toward the earth they calculate the neutron flux which would be produced both during the acceleration and during the slowing down phases of the event. The fluxes of fast neutrons arriving at the earth depend upon the intensity of the energetic particle event and its spectral form which Lingenfelter and Ramaty took to be exponential in rigidity. They found that the time integrated solar neutron spectrum as it
would be observed at 1 A.U. should exhibit a maximum at 20 to 50 MeV. The spectrum will be time dependent due to the finite velocities of the neutrons with the highest energy neutrons arriving ~700 seconds after emission from the sun. As an example, they calculated the flux of neutrons expected at the earth from the major flare of November 12, 1960 and found a peak neutron flux ranging from 2.4 to 33 neutrons cm$^{-2}$ sec$^{-1}$ depending upon what they took for the fraction of solar energetic particles escaping from the sun and upon the amount of material traversed by these particles during acceleration at the sun. These are two to three orders of magnitude greater than the >10 MeV equatorial background flux expected at the top of the atmosphere from CRAND.

3. Atmospheric and Cosmic Gamma Rays

In addition to the neutrons discussed above, there are large fluxes of high energy gamma rays present near the top of the atmosphere. In the 1-10 MeV region, in fact, gamma rays outnumber neutrons by about ten to one. A very few of these are incident on the top of the atmosphere as part of the primary galactic cosmic ray component. The majority are of secondary origin being produced in the atmosphere via the Bremsstrahlung process [Puskin, 1970]. In the following discussion, we will be primarily interested in gamma rays in the energy region between 1 and 10 MeV. Puskin has made a detailed study of the atmospheric gamma ray environment in the energy range 0.3 to 10 MeV at an
altitude of 3.5 mb at 41° latitude. He finds 84% of the 0.3 - 10 MeV photon flux at 3.5 mb is due to Bremsstrahlung from re-entrant albedo electrons and 15% of the gamma ray flux from positron annihilation, this latter 15% being concentrated in the 0.3 - 0.51 MeV range. The flux of gamma rays produced by Π° decay was found to be less than 1% of the 7 - 10 MeV Bremsstrahlung flux. Puskin's calculated spectrum is shown in Figure 2 along with the results of some recent experimental observations. Note that experimental spectra are energy loss spectra and are not unfolded incident photon spectra.

As mentioned above, a few of the atmospheric gamma rays at balloon altitude (~5 g/cm²) will be primary in the sense that they are part of the diffuse cosmic gamma ray flux as measured by Arnold, et al. [1962], Metzger, et al. [1964], and Vette, et al. [1969]. There exists some controversy as to the exact shape of the diffuse cosmic gamma ray spectrum; an abrupt flattening of the spectrum was observed by Ranger 3 [Arnold, et al., 1962] which was not confirmed by the later Ranger 5 flight [Metzger, et al., 1964].

Furthermore, a more moderate flattening at about 2 MeV has been reported by Vette, et al. [1969]. In any case, Puskin makes the point that the atmospheric background is less than an order of magnitude greater than the diffuse space flux at 3.5 mb, and that in fact the downward flux of photons at this altitude is predominately cosmic, being a factor of 5 above the downward directed local photon flux.
CHAPTER III. EXPERIMENTAL TECHNIQUES

1. Detection Schemes

Neutrons are inherently difficult to measure by their very nature. That they were not even discovered until forty years ago attests to this fact. Being uncharged, neutrons do not interact with matter via a Coulomb interaction. Hence, they cannot be detected directly. All present techniques to detect neutrons do so by measuring other ionizing particles which are produced by collision processes or by nuclear interaction of neutrons with matter. In this section we will briefly review the various schemes for detecting fast neutrons ($E_n \geq 1$ MeV). Generally speaking, detection of lower energy neutrons is accomplished by moderating the neutrons to thermal energies where they may subsequently be captured by a nucleus with the emission of a charged particle which is then counted by some type of gaseous ionization counter. The thermal neutron capture cross sections are very large, for example, for Boron-10 $\sigma_{th} = 3,770$ barns and for Helium-3 $\sigma_{th} = 5,000$ barns, which results in very high thermal neutron counting efficiencies [Sharp, 1964]. Fast neutrons may be detected by nuclear emulsions, spark chambers, solid state detectors, and proton recoil scintillation counters with varying degrees of efficiency, energy resolution, and temporal and directional resolution.
In nuclear emulsions, the neutrons undergo reactions, either with a radiator or with the nuclei contained in the emulsion. Such an interaction may result in the formation of a nuclear "star" in which the compound nucleus, formed as a result of the interaction, breaks apart emitting several charged fragments. These fragments leave ionization tracks in the emulsion which after development may be analyzed to determine what took place. Such an analysis yields only very crude information on the energy or on the direction of travel of the incident neutron and gives no information regarding arrival time.

A second type of "track" detector, so called because it leaves a visible track along its path of travel, is the multiwire spark chamber. In this device a gridwork of high resistance wires are held at a very high potential just below the voltage necessary to give rise to spontaneous breakdown. When an ionizing particle passes through this wiregrid, the resultant ionization of the gas between the wires lowers the breakdown voltage to the point where a spark occurs along the ionization trail of the incident particle. Hence, as the particle passes through the chamber, a series of sparks forms along its path. If at the instant of sparking, the chamber is photographed from two orthogonal directions, it becomes possible to accurately determine, from the photographs, the direction of travel of the particle. By placing such a chamber in a magnetic field, or by placing scintillators or other energy sensitive detectors above and below the spark chamber, it becomes possible to determine the
energy of the incident particle. Obviously, in the case of neutrons, a radiator must be utilized to produce recoil protons, since the neutrons themselves are not ionizing.

This leads us to consider other recoil detection schemes in which some type of hydrogenous material is placed in front of the neutron beam. Neutrons of energy up to about 10 MeV kinetic energy scatter isotropically from hydrogen, producing a proton recoil whose kinetic energy may take on any value up to the kinetic energy of the incident neutron dependent only upon the scattering parameters of the collision.

The most common recoil type detector presently in use is the proton recoil scintillation counter. In this device, the usual technique is to combine the functions of the radiator and the scintillating medium into one material. Certain plastics and organic compounds such as anthracene and stilbene as well as organic liquids serve this purpose well. In the present case, an organic liquid is utilized. This material, NE-213, manufactured by Nuclear Enterprises, Ltd. of San'Carlos, California, contains only hydrogen and carbon with a ratio of the number of H atoms to the number of C atoms of 1.213. In such a scintillation counter, the neutron interacts predominately with the hydrogen atoms, producing a recoil proton which then ionizes and excites the scintillating medium to produce a light pulse which is detected by the photomultiplier tube. The amount of light produced in the scintillator, and hence the pulse height of the signal at the base of the photomultiplier, are directly
related to the kinetic energy of the recoil proton. Although this relationship is not strictly linear, as is the case with electrons, it has been extensively studied and is quite well known. [Birks, 1951a,b; Batchelor, et al., 1961] This response is shown in Figure 3 as determined by a number of investigators. In this figure the proton energy response is plotted in terms of the equivalent light output for a given electron energy. This is the easiest form to work with since the absolute light output is difficult to measure.

Solid state detectors can also be used as recoil proton detectors. In this case a thin hydrogenous radiator is deposited on the face of the semiconductor. The recoil proton's energy resolution is excellent with resolutions on the order of 50 KeV at 10 MeV being reported [Dearnaley, et al., 1961]. The use of these detectors for fast neutron detection is however limited to applications where the expected neutron flux is much larger than found at the top of the atmosphere. This is due to the limited efficiencies combined with the small counting areas which are obtainable with such detectors.

In all of the above mentioned devices where the energy of the recoil protons from neutron elastic scattering is measured, the energy spectrum of the incident neutrons may be unfolded from the proton recoil energy spectrum. Several methods have been devised for this unfolding process and are described in detail in the next chapter.
2. Description of Detector

The detector system will be described only briefly here. For a more complete description the reader is referred to St. Onge [1968] and St. Onge and Lockwood [1969a,b].

The basic neutron/gamma ray detector shown in the block diagram of Figure 8 consists of a liquid scintillation solution, NE-213 (purchased from Nuclear Enterprises, Inc.) contained within a cylindrical glass cell of interior dimensions 4.65 cm diameter by 4.60 cm length. At the top of the cell is a small expansion chamber connected to the main cell by means of a capillary tube. The cell is filled with NE-213 such that at all reasonable temperatures the main cell remains completely filled with scintillant. The scintillator is viewed by an RCA 8575 photomultiplier which has been specifically selected for low noise. The bleeder string at the photomultiplier base is a low current design based upon the recommendations of R.C.A. but with a few modifications designed to enhance the pulse shape discriminating properties of the detector. The pulse shape discriminator is connected to the photomultiplier anode and uses a 50 Ω "Z-Match" miniature transformer to provide identical but opposite polarity pulses which are then operated on by integration and attenuation circuits and subsequently recombined to form a signal whose height is dependent upon the incident pulse shape. This signal is then put through a preamplifier, amplifier, and delay and forms the dL/dt pulse for the inflight bi-di-

mensional pulse height analyzer. The full energy (\(\int dt\)) pulse is taken from dynode eleven of the fast photomultiplier and after preamplification and amplification is single channel analyzed. The single channel analyzer is set to pass pulses whose height falls within the broad energy range of interest for the detection system. Those "L" pulses which fall within the range of the single channel analyzer are then delayed so that they arrive at the bi-dimensional analyzer in coincidence with the "dL" pulse generated by the same event. The pulse height analyzer forms a six bit binary word for each "L" and "dL" pulse assigning a channel number from 0 to 63 to each pulse according to its amplitude. The pulse height analyzer also generates three identification bits, checks parity, and assigns a parity bit, if necessary. These 16 bits are arranged serially and transmitted to ground. Thus, each event in the neutron/gamma ray detector is assigned a unique position on a 64 x 64 matrix.

In order that the gain of the system can be continuously monitored both during flight and during ground operations, a radioactive calibration source is built into the system. The source consists of a small amount of Am\(^{241}\) mounted in contact with a 3mm diameter x 3mm NaI(Tl) scintillation chip\(^*\). This light pulser is mounted in contact with the top face of the liquid scintillation cell and provides a light signal whose intensity and rate is extremely

\*Supplied by the Harshaw Chemical Company, Solon, Ohio
stable. The light pulse emitted by this pulser has a pulse shape characteristic of NaI(Tl) and is therefore able to be pulse shape discriminated from those events in the liquid scintillator. On the output pulse shape-pulse height matrix it provides a sharp distribution containing two peaks which are well separated from events initiated in the liquid scintillator.

The neutron/gamma ray detector including pulse shape discrimination circuit, preamplifiers and high voltage power supplies is totally enclosed in a NE102 (purchased from Nuclear Enterprises, Inc.) plastic anticoincidence shield to reject events due to charged secondary and primary cosmic rays. This charged particle shield has a cylindrical midsection of 28.6 cm interior diameter, 1.588 cm thick walls and a height of 15.24 cm. Each end of the cylinder is capped with a hemispherical NE102 dome, each of which is viewed from the inside by an RCA C70132A type photomultiplier with hemispherical photocathode. The dome sections are constructed such that the centers of curvature for the interior and exterior surfaces are displaced a distance of .476 cm from each other along the symmetry axis. The effect of this offset is to make the dome increasingly thicker as the distance from the apex is increased. This was done to enhance the ability of the system to reject pulses from minimum ionizing charged particles which pass through the dome at large distances from the photomultiplier tubes. Recall that the energy deposited by a minimum ionizing particle traversing some material increases in direct
proportion to the thickness of that material. The output of each of the two charged particle photomultipliers is connected to a sum-coincidence circuit (see Figure 8) such that either a single large pulse from only one photomultiplier or two smaller pulses, one from each photomultiplier in coincidence, may trigger the charged particle rejection circuitry. The combination of the sum-coincidence circuit and the varying shield thickness along with adiabatic light piping makes it possible to achieve the almost 100% rejection efficiency required for this system using only two photomultiplier tubes. The count rate of the charged particle shield is scaled by 200 and transmitted to ground as are the rates of the neutron/gamma ray detector both including and excluding charged particle events. (The latter two rates, however, are only scaled by a factor of 20 before transmission.)

In addition to the above mentioned data housekeeping information, such as battery voltages, regulator voltages and package temperatures at several points, is also telemetered to the ground tracking station.

Some changes have been made to the system since its initial flight in September 1968 as reported by St. Onge [1968] and St. Onge and Lockwood [1969a,b]. Most of these have been minor and did not include any modifications to the detector module itself except for the replacement of a charged particle photomultiplier which became noisy during the fall of 1968. The only major change to the
system was made in the electronics package. All amplifiers, gating and delay circuits and the charged particle sum-coincidence circuits in the central electronics package were replaced during the spring of 1969 before the current series of balloon flights began. The changes were made in order to reduce the number of commercial nuclear instrument modules being flown which reduces power consumption and thereby increases the maximum allowable flight time.
3. Pulse Shape Discrimination

The experimental technique employed in this work relies on the fact that in organic scintillators the shape of the light output pulse produced by the interaction of the charged particle in the scintillator is a function of the species of ionizing particle. The scintillation pulses decay with a combination of decay time constants. Because amplitude ratios of fast and slow components of the relaxation are different for different types of particles, it becomes possible to discriminate between the different types [Owen, 1959]. The ability of the high gain photomultiplier tube to faithfully reproduce this pulse shape in an electrical pulse allows one to make use of this pulse shape difference to discriminate the different particle types, for example, to discriminate between neutrons and gamma rays.

For the NE-213* liquid organic scintillator used here, each light pulse is composed of two primary components: a large fast component having a decay time of 3.16 nsec, and a smaller slow component with a characteristic decay time of 270 nsec [Kuchnir and Lynch, 1969]. Approximately 50% of the integral light output in a given pulse is contained in each component. However, for different ionizing particles, the relative amplitudes of these two compounds differ. Thus, when the scintillator is excited by an electron (arising from Compton scattering of an incident gamma ray), the amplitude ratio of the fast to slow components is much smaller than,
for example, if the scintillator had been excited by a proton (arising say from an n, H collision). It has recently been demonstrated [Kopsch and Cierjacks, 1967] that the pulse shape discrimination technique can also be used to identify α-particles.

Since the intensities of the slow and the fast components depend on the mass and charge of the particle absorbed in the scintillator, it seems likely to expect that particles of even higher charges may also be separable with a good pulse shape discriminating system. Especially when the scintillator is itself used as a target, it should then be possible to observe those charged particles which arise from nuclear reactions with the target materials. Thus, for neutrons incident on a target composed only of hydrogen and carbon, it should be ideally possible to observe 1) recoil protons from the elastic scattering of neutrons on hydrogen as well as protons from the C$_{12}$(n,p)B$_{12}$ reaction, 2) α-particles from a variety of carbon interactions of the type C$_{12}$(n,α)Be$^9$, or C$_{12}$(n,n'3α), 3) recoil beryllium from the C$_{12}$(n,α)Be$^9$ reaction, 4) boron nuclei from the C$_{12}$(n,p)B$_{12}$ and finally, 5) recoil carbon nuclei and scattered neutrons from the elastic scattering of neutrons on carbon. Let us consider each of these possibilities in turn.

Protons

In an elastic scattering event with a fast neutron on a free hydrogen atom, the neutron may transfer any fraction of its energy from 0 to 100% to the proton of the hydrogen.
nucleus with equal a-priori probabilities. Thus, a 10 MeV neutron undergoing elastic scattering on hydrogen will, with equal probability, produce a proton with any energy up to 10 MeV. For incident neutrons with energy less than about 10 MeV this scattering is isotropic in the center of mass system. An ideal proton recoil spectrum from a monoenergetic beam of neutrons is shown in Figure 4, curve A. Figure 4, curves B and C, illustrate the departures from the ideal recoil spectrum which arise from nonlinearities, multiple scattering, and finite size effects, which will be discussed later.

Protons may also be produced in the organic scintillator by means of the neutron-proton exchange reaction on carbon. The cross sections for this reaction are shown in Figure 5. Note that the threshold occurs at 13.6 MeV, rises to a peak of 140 mb at 25 MeV, then drops off slowly to 100 mb at 300 MeV [Kurz, 1964]. It is evident that this process can contribute to events to the "recoil proton" curve which would be misinterpreted as true recoil protons from elastic scattering on hydrogen. To determine the magnitude of this effect, we must calculate the number of interactions of this type which are to be expected during a balloon flight. For any given interaction the number of neutrons which remain in a beam of initial intensity $N_0$ after traversing a distance $x$ through a target is given by

$$N = N_0 e^{-\rho x \sigma(E)}$$  \hspace{1cm} (III-1)  

where $\rho$ is the density of target nuclei, in this case carbon
and $\sigma(E)$ is the cross-section of the particular reaction under consideration. Thus, the number which interact in traversing the length $L$ of scintillator is clearly

$$N(E) = N_0(E) \left[1 - e^{-\rho x \sigma(E)}\right] \quad (III-2)$$

If one uses a neutron leakage spectrum similar to that obtained by Lingenfelter [1963], namely, $N(E) = 0.52 E^{-2.0}$ and the cross-section shown in Figure 5, then the number of interactions as a function of neutron energy can be calculated. The total integrated number of protons due to neutrons from 14 MeV to 300 MeV arising from the $^{12}(n,p)^{12}$ reaction is thus 450 for a flight of 7.8 hours duration at float at 40° N geomagnetic latitude. Due to the rapidly falling incident neutron spectrum, neutrons above 300 MeV will not contribute significantly to this process. This compares with the actual observation of 24,439 "proton recoils" in our Palestine balloon flight of 7.8 hours duration. Hence, this reaction can be neglected as an important source of "contamination" to our proton recoils being only 1.8% of the true proton recoils.

The same technique can be used to calculate the number of true hydrogen recoil protons which are to be expected on this same flight. Using the $n-p$ cross-section given in Figure 5 and the neutron spectrum assumed above, one finds that for neutrons in the interval 3-21 MeV there should be 29,636 proton recoil events produced in 7.8 hours. Neutrons above about 21 MeV do not contribute significantly
due to the exponentially falling neutron spectrum and the rapidly decreasing cross-section. This result is in excellent agreement with the 24,439 events actually observed.

Alpha Particles

Single alpha particles may be produced in the organic scintillator through the reaction $^{12}\text{C}(n,a)^{9}\text{Be}$. Since alpha particles have a different excitation and ionization density than protons, they will give rise to scintillation pulses which have a distinct pulse shape. Hence, this interaction will not contaminate the proton recoil data but instead will occur at a different position on the output matrix as shown in Figure 7. It is interesting to calculate the number of events which would be predicted and to compare this to the number actually observed during the flight. Again, using equation III-2 with the appropriate cross-section for the $^{12}\text{C}(n,a)^{9}\text{Be}$ reaction (Figure 5) and the Lingenfelter neutron leakage spectrum, we find that 193 interactions should occur from neutrons between 14 MeV and 30 MeV, which will produce alpha particles. Neutrons below 14 MeV cannot produce alpha particles whose energy lies above the 8.4 MeV alpha particle threshold of our detector. Furthermore, not all of these alpha particles will have sufficient energy to lie above the threshold of the detector. During the Palestine flight, we counted 3,370 events which we tentatively attributed to alpha particles.

There are a variety of modes in which three alpha particles may be produced by a fast neutron interacting with
carbon-12. Among these are:

1. $^{12}\text{C}(n,a)^9\text{Be}^*(n')\text{Be}^8*(2a)$
2. $^{12}\text{C}(n,a)^9\text{Be}^*(a)^5\text{He}(n'a)$
3. $^{12}\text{C}(n,n')^{12}\text{C}^* (a)^8\text{Be}^*(2a)$
4. $^{12}\text{C}(n,n')^{12}\text{C}^* (3a)$
5. $^{12}\text{C}(n,n' 3a)$

According to G. M. Frye, et al. [1955] the favored modes are 3 and 5 above. Regardless of which mode actually occurs, this detector should not be able to distinguish among them because the various excited states are very short-lived. The detector is unable to resolve these very short time intervals. Hence, in any case, the scintillator sees the three alpha particles occurring essentially simultaneously. Since the alpha particles have such a very short range in the scintillator, the total ionization density will be much larger than that due to a single alpha particle. Hence, we would expect to see these events as a distinct track on our output data matrix. We have indicated in Figure 7 the location of those n-C interactions which lead to the production of three alpha particles. It is worthwhile to calculate the number of events of this type which are to be expected. The cross-section for the $^{12}\text{C}(n,n' 3a)$ reaction is shown in Figure 5. Performing the same calculations as before, we find that for a neutron spectrum of $0.52E^{-2.0}$ we would expect 767 events due to neutrons in the range 15 to 100 MeV during a flight of 7.8 hours duration. This is within a factor of two of
the 396 events actually observed in the Palestine balloon flight.

The results of all of the above calculations are summarized in Figure 6 which shows the relative importance for neutron absorption of the four interactions discussed. Each curve indicates the number of neutrons $\text{cm}^{-2}\text{sec}^{-1}\text{MeV}^{-1}$ absorbed from an incident neutron energy distribution of the form $E^{-2.0}$. For neutrons whose energy exceeds about 15 MeV the carbon interactions constitute a significant fraction of the events.

Heavier Nuclei

It is unlikely that a significant number of nuclei heavier than helium could be produced within the scintillator by reactions of carbon with fast neutrons. This is due to the large kinetic energy required by such a heavy particle to create a large enough ionization excitation to be observed. For example, in elastic scattering of neutrons on carbon, the neutron can transfer, at most, only 28% of its energy to the carbon nucleus. Furthermore, for a carbon nucleus to produce a light output in our scintillator equivalent to a 3 MeV proton (the lower threshold of our detector), it would be required to have a kinetic energy exceeding 75 MeV [Verbinskii, et al., 1968]. Thus, the required incident neutron energy would have to have been in excess of 260 MeV. For a neutron spectrum of the shape $0.52 E^{-2.0}$ the number of neutrons/cm$^2$sec greater than 260 MeV is
\[ \int_{260}^{\infty} 0.52 \cdot 10^{-2} \cdot 0 \, dE = 2 \times 10^{-3} \, \text{cm}^{-2} \, \text{sec}^{-1} \]

So that in a 7.8 hour flight, only 1554 neutrons of \( E > 260 \) MeV would strike the detector. Now with an interaction probability of \( (1 - e^{-px}) = 3.34 \times 10^{-2} \) we find that only 52 carbon recoils would be produced.

The number of interactions leading to the production of protons and alpha particles can be calculated for any incident neutron spectrum. As an alternative to the Lingenfelter type spectrum used above one may apply the neutron spectrum recently published by Preszler, et al. [1972]. They report a constant neutron leakage energy distribution of \( 4.0 \times 10^{-3} \) neutrons \( \text{cm}^{-2} \, \text{sec}^{-1} \, \text{MeV}^{-1} \) from 15 to 55 MeV with a falling spectrum at energies \( >55 \) MeV which may be described by a powerlaw of the form \( 12 \cdot E^{-2} \). If a spectrum given by \( 0.3 \cdot E^{-1.6} \) is chosen for the entire range 3 to 15 MeV then the number of events due to the various possible interactions in the scintillator can be calculated. Using the same cross sections and time as used in the previous calculations we obtain the results summarized in Table 2. Note that the combination spectrum produces more interactions of all types but that the \( ^{12}\text{C}(n,p)^{12}\text{B} \) and \( ^{12}\text{C}(n,n'3\alpha) \) reactions are increased by a factor of ten or more by this spectrum. This is due to the larger number of high energy neutrons present in the combination spectrum combined with the relatively large cross sections for these two reactions at high neutron energies.
TABLE 2: The number of events expected from n-H and n-C interactions over the indicated energy ranges for three different incident neutron spectra during 7.8 hours at float altitude at 40°N geomagnetic latitude.

<table>
<thead>
<tr>
<th>Assumed Neutron Spectra</th>
<th>0.52 E(^{-2.0})</th>
<th>0.20 E(^{-2.0})</th>
<th>Combination* Spectrum</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H(n,n')p</td>
<td></td>
<td></td>
<td></td>
<td>24,439</td>
</tr>
<tr>
<td>3&lt;En&lt;100MeV</td>
<td>29,636</td>
<td>11,400</td>
<td>43,069</td>
<td></td>
</tr>
<tr>
<td>C(^{12}) (n,p)B(^{12})</td>
<td>449</td>
<td>173</td>
<td>5,196</td>
<td></td>
</tr>
<tr>
<td>14&lt;En&lt;300MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(^{12}) (n,a)Be(^{9})</td>
<td>193</td>
<td>74</td>
<td>550</td>
<td>3,370</td>
</tr>
<tr>
<td>14&lt;En&lt;55MeV</td>
<td></td>
<td></td>
<td></td>
<td>(tentative ident.)</td>
</tr>
<tr>
<td>C(^{12}) (n,n'3a)</td>
<td>767</td>
<td>295</td>
<td>6,944</td>
<td>396</td>
</tr>
<tr>
<td>15&lt;En&lt;300MeV</td>
<td></td>
<td></td>
<td></td>
<td>(tentative ident.)</td>
</tr>
</tbody>
</table>

\*\{ 
0.3 E\(^{-1.6}\) (3<E<15 MeV) \\
4.0 \times 10^{-3} (15\leq E<55 MeV) \\
12.0 E\(^{-2.0}\) (E>55 MeV) 
\}
It should be clear from these calculations that this type of analysis is insufficient to enable one to choose either of the assumed spectra over the other by direct comparison with the experimental data. Detailed spectral unfolding is thus necessary. Furthermore, the above analysis does not provide sufficient information to unambiguously identify the unknown tracks (tentatively labeled a and 3a) which appear on the matrix of Figure 7. In order to identify these events, it will be necessary to combine the above type of analysis with experimental data on monoenergetic neutrons from a high energy accelerator.
CHAPTER IV

SPECTRAL UNFOLDING TECHNIQUES

In the recoil proton scintillation spectrometer a pulse height spectrum is obtained which is representative of the energy loss distribution of proton recoils in the scintillator. This energy loss distribution is in turn related to the incident neutron energy distribution. All spectral unfolding techniques must incorporate these relationships in order to convert the measured pulse height spectrum into a true incident neutron spectrum. Two general techniques have evolved for the unfolding of neutron spectra. The differentiation technique makes use of the analytical relationship between the recoil proton spectrum and the incident neutron spectrum. The second technique, or response matrix technique, employs the direct, usually empirically determined, response of the total detection system to a series of monoenergetic neutron sources. In both techniques direct experimental determinations as well as Monte Carlo type calculations may be used. Before discussing these particular unfolding methods, we shall review the various factors which give rise to a particular pulse height distribution.

As previously pointed out a fast neutron which scatters elastically with hydrogen may transfer any fraction of its energy from 0 to 100 percent to the recoil proton with
equal probability. Thus one would expect the pulse height spectrum from a monoenergetic incident neutron beam to be a rectangular distribution as shown in Figure 4, curve A. In fact such an ideal spectrum is not obtained in practice as shown in curves B and C of the same figure. Departures from the ideal recoil distribution are due to non-isotropy of the n-p scattering cross-section which becomes important above \( \sim 10 \) MeV, scattering from carbon, multiple scattering effects, finite scintillator size, and distortions which result from the nonlinearity of the luminous output of the scintillator as a function of proton energy loss.

If the n-p scattering cross section is isotropic in the center of mass system, then it can be shown that the energy distribution of recoil protons is a rectangular distribution, even though the scattering cross-section in the laboratory system of the detector is not isotropic (see Appendix A).

However, if the cross-section in the center of mass is anisotropic then the proton recoil energy distribution will be given by

\[
\frac{d\sigma_L}{dE_p} = \frac{4\pi}{E_n} \frac{d\sigma_{\text{cm}}}{d\theta_{\text{cm}}} \tag{IV-1}
\]

as derived in Appendix A. For the non isotropic case \( d\sigma_{\text{cm}}/d\theta_{\text{cm}} \) will be related to the energy and hence \( d\sigma_L/dE_p \) will be a function of energy.

The presence of carbon in the scintillator makes it possible for an incident neutron of energy \( E_0 \) to initially
scatter from carbon and subsequently produce a recoil proton in a second scattering event with hydrogen. In this case the once scattered neutron will have its energy depressed by the amount which was transferred to the carbon nucleus, a maximum of $0.28 E_0$. Hence the recoil proton spectrum from these events will have a maximum energy of $0.72 E_0$ as opposed to a maximum of $E_0$ had the neutron not scattered from carbon. A second class of multiple scattering events can occur in which the neutron scatters twice with hydrogen. In this case two recoil protons will be produced within such a small time interval that they are recorded as a single event, with an energy equal to the sum of the two proton energies. The resultant energy distribution is dependent on the neutron energy and the crystal size but it is clear that the net effect will be to suppress the occurrence of low energy events and enhance the spectrum at high energies leaving the total area under the spectrum unchanged. Swartz and Owen [1960] performed an approximate calculation and concluded that for "rather small crystals the multiple scattering effects do not drastically change the shape of the pulse height spectrum since scattering from carbon and hydrogen enhances the low energy region, while double scattering from hydrogen shifts counts toward the high energy region." This conclusion seems to be supported by Batchelor, Gilboy, Parker, and Towle [1961] who showed pulse height distributions for 0.7 to 14 MeV neutrons derived from Monte Carlo calculations with experimental verification, for a 2 inch by 2 1/2 inch NE213 scintillator. They found that for their scintillator
double scattering with hydrogen becomes important at energies less than 2 MeV. As the incident neutron energy increases there is a shift of pulses from high to low light output. This, they pointed out, is due to the high relative importance of multiple scattering at low energies in comparison with the nonlinear pulse height response which is the dominant factor at high energies.

The finite size of the scintillator may also contribute to deviation from the ideal recoil pulse height spectrum. Because of the finite range of a recoil proton, some protons may escape from the scintillator before depositing all of their energy. This will have the effect of enhancing the low energy portion of the pulse height spectrum and suppressing the high energy distribution. Obviously the importance of this effect is also a strong function of the incident neutron energy and the size of the scintillator becoming increasingly more important as the size of the scintillator is reduced. It should by now be clear that for a given neutron energy there exists an ideal detector size such that the distortion effects due to multiple scattering on the one hand, and edge effects on the other are both minimized and the resulting distribution is closest to the ideal. M. E. Toms [1970] has lumped the effects together into one quantity called the shape correction factor. She found that for a given scintillator diameter the slope of the shape correction factor becomes less as the length of the scintillator approaches its diameter and that the variation in the shape correction factor is acceptable when a detector's length is nearly equal to or
some what greater than its diameter. Batchelor, et al. [1961] also found for a 2 inch diameter by 2 1/2 inch NE213 scintillator that edge effects are negligible for neutrons up to 14 MeV. This is consistent with the fact that the energy of a proton whose range is 2 inches is greater than 70 MeV using the empirical result of Toms [1970]:

\[ R_m = 1.7382 \left[ E + 0.15045\right]^{1.8194} \text{mg/cm}^2 \]  

(IV-2)

where \( R_m \) is the range in NE213 of a proton of energy \( E \). Or putting it another way a 10 MeV proton has a range of only 1.3mm in NE213.

Let us now turn to the final factor affecting the recoil energy distribution; namely, that due to nonlinearity of the luminous output of the scintillator as a function of proton energy loss. It is well known that for electrons the light output of a scintillator is directly proportional to the energy lost by the electrons. This is not true in the case of protons, as illustrated in Figure 3. This non-linear response has been studied in detail and can be represented by the semi-empirical formula of Birks [1951a,b]:

\[ \frac{dS}{dx} = \frac{A \frac{dE}{dx}}{1 + kB \frac{dE}{dx}}. \]  

(IV-3)

where \( S \) is the luminous output of the scintillator, \( x \) is the path length of the particle and \( E \) is the particle energy. By dividing through both sides by \( A \) and defining \( P = S/A \) we have
\[ \frac{dP}{dE} = \frac{A^{-1}}{(1 + k_B \frac{dE}{dx})} \]

as given in Swartz and Owen [1960]. For electrons \((E_e > 125\) keV) the energy loss is so small that the \(k_B dE/dx\) term can be neglected and then \(dP/dE = 1\) or \(P = E_e\) where \(E_e\) is the electron energy. For protons of a few MeV of energy \(dE/dx\) is not small and the full expression must be used to find \(P\) as a function of \(E_p\). Now we can see the rationale behind plotting proton energy versus electron energy for equivalent pulse heights as was done in Figure 3.

In addition to the above mentioned effects tending to distort the recoil energy distribution is that due to statistical fluctuations inherent in both the scintillator and in the photomultiplier tube. The effect is to produce a Gaussian distribution of pulse heights centered about a mean value for each proton energy. Statistical fluctuations smear out any sharp features which may exist in the neutron spectrum being measured and contribute to the overall broadening of the system's resolution.

1. Differentiation Technique

As discussed in the previous section the recoil proton energy spectrum produced in an organic scintillator by interaction of monoenergetic neutrons is ideally a rectangular distribution with high energy cutoff at the energy of the incident neutron. Hence for a continuous spectrum of neutrons the neutron spectrum is proportional to the negative first derivative of the proton recoil spectrum. Of course the
distortion effects discussed in the previous section will alter this ideal relationship. However, in practice, the differentiation technique can be used with the distortions being applied as correction factors after the differentiation.

For a given neutron spectrum, the proton recoil spectrum which is produced is given by [Staub, 1953]

\[
\frac{dN_p}{dE_p} = N_H \int_{E_p}^{\infty} \sigma(E_n) \frac{dN_n}{dE_n} \frac{dE_n}{E_n} \quad (IV-5)
\]

where \(E_n\) is the neutron energy, \(E_p\) the proton energy, \(dN_p/dE_p\) the number of protons per unit proton energy interval, \(dN_n/dE_n\) is the number of neutrons per unit area per unit neutron energy interval incident on the scintillator, \(N_H\) the number of hydrogen atoms in the scintillator and \(\sigma(E_n)\) is the neutron-proton scattering cross-section.

Differentiating one obtains

\[
\frac{d}{dE_p} \left[ \frac{dN_p}{dE_p} \right] = N_H \frac{d}{dE_p} \int_{E_p}^{\infty} \sigma(E_n) \frac{dN_n}{dE_n} \frac{dE_n}{E_n} \quad (IV-6)
\]

Recalling a fundamental calculus theorem:

\[
\frac{d}{dt} \int_{a}^{t} f(x)dx = f(t)
\]
then we find

\[
\frac{d^2N_p}{dE_p^2} = - N_H \sigma(E_n) \frac{dN_n}{dE_n} \bigg|_{E_n=E_p}
\]  

(IV-7)

or

\[
\frac{d^2N_p}{dE_p^2} = - \frac{N_H \sigma(E_p) dN_n}{E_p} \bigg|_{E_p}
\]  

(IV-8)

Hence, the neutron spectrum is given by

\[
\frac{dN_n}{dE_n} \bigg|_{E_p} = - \frac{E_p}{N_H \sigma(E_p) dE_p^2} d^2N_p
\]  

(IV-9)

So that we have just demonstrated that the neutron spectrum is proportional to the negative rate of change of the proton recoil spectrum with energy. Now however, a further modification is necessary. The response of the organic scintillator is a non-linear function of proton energy. Hence, the proton spectrum is related to the pulse height \(L\), by \(\frac{dN_p}{dE_p} = \frac{dN_p}{dL} \frac{dL}{dE_p}\). Thus the neutron spectrum is given in terms of pulse height by

\[
\frac{dN_n}{dE_n} \bigg|_{E_p} = - \frac{E_p}{N_H \sigma(E_p)} \left[ \frac{d}{dL} \left( \frac{dN_p}{dL} \frac{dL}{dE_p} \right) \frac{dL}{dE_p} \right]
\]  

(IV-10)

where \(\frac{dN_p}{dL}\) is the number of protons per unit pulse height interval. Note that this expression does not yet include those distortion effects due to second scattering and finite detector size mentioned previously.
Since second scattering and wall effects both depend upon scintillator size they may be treated together. As the scintillator size is increased second scattering becomes more important while wall effects become less important. Broeck and Anderson [1960] have obtained an approximate formula which corrects for these effects

\[ B = 1 - 0.780 \left( \frac{R_m}{L} \right) + 0.090 N_H \sigma_H L + 0.077 N_H \sigma_H r \]  (IV-11)

where \( \sigma_H' \) is the value of \( \sigma_H \) at 0.068 E, \( R_m \) is the range of a proton that receives the full neutron energy and \( L \) and \( r \) are the length and radius of the scintillator. The proton range energy relation \( R_m(E) \) obtained by M. E. Toms [1970] for NE213 was given in the previous section.

Finally, since some neutrons will scatter out of the beam in passing through the scintillator an attenuation factor is needed. The attenuation factor has been given by Swartz and Owen [1960] as

\[ f(aL) = \frac{(1 - e^{-aL})}{aL} \]  (IV-12)

where \( a = N_H \sigma_H + N_C \sigma_C \) and \( N_H \) and \( N_C \) are the number of hydrogen atoms and carbon atoms per cm\(^3\) respectively.

Finally combining these all together, we have, for the neutron spectrum

\[ \left. \frac{dN_n}{dE_n} \right|_{E_p} = \frac{E_p}{N_H \sigma_H} \frac{aL}{1-e^{-aL}} \left[ \frac{d}{dL} \left( \frac{dN_p}{dL} \frac{dL}{dE_p} \right) \frac{dL}{dE_p} \right] 

(IV-13)
where the quantity in square brackets is the slope of the proton pulse height distribution at energy $E_p = E_n$.

2. **Matrix Inversion Technique**

The matrix inversion method uses experimentally measured response functions instead of the ideal rectangular response.

The problem in spectral unfolding is the solution of the homogeneous Fredholm Equation given by Sanna and Obrien [1971] as

$$N(E_p) = \phi(E)K_y(E)dE_n$$

for an energy spectrum $\phi(E)$ where $N(E_p)$ is the measured parameter (pulse height spectrum) and $K_y(E)$ the response function. This expression can be approximated by a matrix equation [Brunfelter, Kockum, and Zellerstrom, 1966] which may be solved numerically

$$<N> = M<\phi>$$

$<N>$ and $<\phi>$ are column vectors and $M$ is a square matrix. The elements of each are:

$$N_j = \int_{\Delta E\text{, }p_j} N(E_p) \, dE_p$$

$$\phi_i = \phi(E_\text{, }n_i - \theta \Delta E_\text{, }n_i \mid 0 < \theta < 1)$$
The neutron spectrum, given by the vector $\phi$, is then obtained by multiplying the matrix equation by the inverse matrix $M^{-1}$. Because of statistical fluctuations in the measured pulse height spectrum, the solution to the matrix equation is not unique. Furthermore, oscillations are often produced in the neutron spectrum which are non-physical and again are a result of statistical fluctuations [Brunfelter, et al., 1966].

3. Method of Successive Approximations

A third technique, which is particularly useful if the neutron spectrum being measured is smooth and does not contain much structure, employs a method of successive approximations to the incident spectrum to predict the measured pulse height spectrum. That particular neutron spectrum which produces the best fit to the observations as determined by a weighted Chi-square test is taken as the true atmospheric neutron spectrum. In practice, an initial choice is made of the neutron energy distribution. This spectrum is then used in the right hand side of equation (IV-5) and the integration is carried out numerically by Simpson's 1/3 rule in 0.05 MeV steps. The hydrogen cross sections at every tenth MeV from 1.0 MeV to 20 MeV are taken from the recent tabulation by Horsley [1967] and above 20 MeV from the tabulations of Hopkins [1971] and Kurz [1964]. In order to obtain the

$$M_{ji} = \int_{\Delta E_{p_j}} \int_{\Delta E_{h_i}} dE_p dE_n$$  \hspace{1cm} (IV-18)
hydrogen cross sections at every 1 MeV above 20 MeV it was necessary to interpolate between the values available from Hopkins and Kurz. A three point Lagrange interpolation is used which is more than adequate since the cross section is a smooth slowly decreasing function of energy in this region. The total neutron-carbon cross sections have been obtained from the tabulation of Kurz [1964]. Again three point Lagrange interpolation was used to obtain the value of the cross section at each tenth MeV step from 1 to 20 MeV and at one MeV steps from 20 to 100 MeV. After the integration has been carried out the efficiency and shape correction factors are determined for each energy and are applied to the result to obtain the predicted number of proton recoils versus proton energy. The measured pulse height analyzer channel widths and the known proton energy vs. light output function are used to deduce a pulse height spectrum which is compared to the direct measurement. The goodness of fit of the calculated spectrum to the measured spectrum is tested by a weighted Chi-square technique. Many different spectra may be tested in this manner and those which have the smallest weighted Chi-square values will be the most representative of the incident neutron spectrum.

It should be clear that this unfolding method will not produce one unique spectrum but rather a whole set of solutions. This should not be viewed as a deterrent to applying this technique as it is precisely this range of solutions which exhibits the accuracy to which neutron spectra can be measured with the present or any other recoil proton
scintillation spectrometer. Clearly the true atmospheric spectrum must be somewhere between the upper and lower bounds set by this family of solutions. Further remarks on the error limits which must be assigned to a measurement of the spectral shape will be made in Chapter VII where the results of the present experiment are discussed in light of other measurements.

4. Gamma Ray Unfolding Technique

The unfolding problem for electron recoil data is somewhat different from proton recoil unfolding. The differentiation technique is not applicable since the kernel of the integral equation is a function of the incident gamma ray energy. Furthermore, the use of the inversion technique is limited because of its tendency for producing unphysical results with large oscillations. The method chosen to unfold the atmospheric gamma ray spectrum is a successive approximation technique like that described in the previous section.

For a differential gamma ray flux given by $N_{\gamma}(E_{\gamma},x)$ (photons/cm$^2$ sec MeV) then

$$N_{\gamma}(E_{\gamma},x)dE_{\gamma} \sigma_{T}(E_{\gamma},E_{e})dE_{e}dx \quad (IV-19)$$

is the number of electrons produced in an energy interval $E_{e}$ to $E_{e} + dE_{e}$ by photons in an energy interval $E_{\gamma}$ to $E_{\gamma} + dE_{\gamma}$ in a slab of thickness $dx$ at position $x$ along the symmetry axis of the scintillator where $\sigma_{T}(E_{\gamma},E_{e})$ is the total
differential cross section for production of electrons in the
interval $E_e$ to $E_e +dE_e$. The total differential cross section
is equal to the sum of the differential cross sections for
production of electrons by Compton interactions and by the
pair production process. Integrating over all gamma ray
energies which can produce electrons of energy $E_e$ we obtain

$$N_e(E_e, x) dE_e dx = \int_{E_e - \Delta E_e}^{E_e + \Delta E_e} N\gamma(E, x) dE_e \sigma_T(E, E_e) dE_e dx \quad (IV-20)$$

which is the electron spectrum at $x$ where $n_e$ is the electron
density in the cell. It is not however the electron spectrum
which is measured. Rather it is the pulse height distribu-
tion. If the electron has sufficiently low energy that its
range does not exceed the dimensions of the scintillator then
it will lose all of its energy in the detector and its pulse
height will be directly proportional to the energy lost.
However if the electron escapes before depositing all of its
energy the observed pulse height will be too small. In this
latter case $E_e > k(1-x)$ where $k = \left[ \frac{dE_e}{dx} \right]_{ave}$, the average energy
loss per unit length, $l$ is the length of the scintillator and
$x$ is the distance from the end face of the scintillator where
the electron was created. Here the number of electrons
measured at energy $E_m$ is

$$N_{meas}(E_m, x) dE_m = \int_{E_m(x)}^{E_{\gamma, max}} N(E, x) dE \quad (IV-21)$$
In practice the integrals are rewritten as sums and the integration carried out by computer subject to the electron escape condition. For each gamma ray energy the number of electrons of a specified energy at each position \( x \) are calculated for 1 photon cm\(^{-2} \) sec\(^{-1} \) MeV\(^{-1} \) incident at the top of the cell. These are then summed over all \( x \) to obtain the total electron energy distribution. The result is an \( n \times n \) triangular matrix which when multiplied into a column vector, the elements of which are the number of photons cm\(^{-2} \) sec\(^{-1} \) MeV\(^{-1} \) of the assumed gamma ray spectrum, will yield the expected electron recoil spectrum. This predicted recoil spectrum is then compared to the measured electron spectrum. If they are not in agreement, a new gamma ray spectrum is chosen and the iteration proceeds in this manner until the predicted electron spectrum is found to be in agreement with measurement.

The Compton cross sections needed for these calculations are generated using the Klein-Nishina formula. Pair production cross sections were obtained from the tabulation of Johns, et al. [1954].
CHAPTER V

BALLOON FLIGHTS

The detector described in Chapter III was flown in five balloon flights during 1969 and 1970. In order to minimize the effects of local production of neutrons by charged primary and secondary cosmic rays in the detector and its support equipment, the gondola is divided into three separate modules. The detection module contains only the neutron/gamma ray (n/γ) detector, the charged particle shield and photomultipliers, and the preamplifiers, high voltage converters, and pulse shape discrimination circuit, all of which must necessarily be located in close proximity to one another. The unique feature employed in this detection module is that the charged particle scintillation shield totally encloses all of the above mentioned detectors and electronics [St. Onge and Lockwood, 1969b]. This minimizes the local production effects since the n/γ detector is gated off whenever a charged particle passes through the anti-coincidence shield making it impossible for charged particles to produce neutrons in this equipment which will be counted by the n/γ detector.

The remaining electronics support equipment which includes amplifiers, gating circuits, count rate scalars, pulse height analyzer and telemetry equipment is housed in the electronics module. During the balloon flights this module is suspended below the detector module at a distance
of 13 to 25 feet dependent upon launch restrictions. Finally the batteries and transmitter are contained in a third module which during flight is attached to the bottom of the electronics module.

The first flight in this series was launched from the National Center for Atmospheric Research, Scientific Balloon Flight Station at Palestine, Texas on April 22, 1969 (Flight Number 460-P). The total scientific payload weight was 354 pounds with an additional 236 pounds ballast and NCAR control instruments which were located alongside the battery module. Several minor failures were experienced during this flight. By approximately 90 minutes after launch the temperature in a small electronics package housing the count rate scalars had reached 0°C resulting in a loss of count rate data for the charged particle shield and the gated count rate in the n/γ detector. At approximately 1200 CST the PSD-pulse height data train began dropping bits and after being satisfied that the problem was not likely to be corrected the flight was terminated at 1441 CST. Upon subsequent analysis of the data it was determined that the PSD-pulse height data was not affected until after 1100 CST and that the loss of scalar data did not prevent analysis of the flight data up to this time. The temperature problem was solved in future flights by decreasing the amount of surface area of the small electronics package in direct thermal contact with the skin of the electronics module.

A second flight of the system was performed on
April 3, 1970. In addition to the experiment being reported here were included two additional experiments intended to complement the data from the 2 inch Fast Neutron Detector (FND). One was a prototype three inch fast neutron scintillation detector and the second was a moderated $^3$He neutron counter similar to those flown in a series of rocket flights from 1965 to 1967 [Lockwood and Friling, 1968]. The moderated $^3$He counter performed as expected and was flown as a companion detector on each of the remaining balloon flights in this series. This flight was also launched from the NCAR balloon base at Palestine, Texas (NCAR Flight Number 538-P) and remained at float for nearly eight hours before being terminated by radio command after exceeding telemetry range. For this flight a downwind tracking station was set up in Laurel, Mississippi. This station yielded an additional three hours of useful data. The flight gondola configuration is shown in Figure 9. Again great care was taken to minimize local production effects. The moderated $^3$He counter and the three inch FND were suspended at the ends of an eight foot suspension bar below which was suspended the 2 inch FND at a distance of seven feet. The electronics and battery modules were suspended 11 feet below the center of the detector module and an additional electronics module (containing batteries and support electronics for the $^3$He and 3 inch detectors), as well as the NCAR electronics package, were placed on either side of the battery module. A hopper containing 300 pounds of ballast was placed below the battery module. The total scientific payload weight
(excluding ballast but including NCAR electronics) was 595 pounds. The 2 inch FND, as well as the He\(^3\) counter performed flawlessly during this entire flight.

The third flight of this detector and the He\(^3\) counter was conducted on July 5, 1970 from Ft. Churchill, Manitoba, Canada. For this flight the detector module and the He\(^3\) counter were fastened to the ends of the eight foot cross bar with the electronics and battery modules suspended below the bar at a distance of 24 feet. The total weight (without ballast) was 637 pounds of which 527 pounds was contained in the lower gondola portion 24 feet below the detectors. Again both detectors performed optimally and the flight was terminated after exceeding telemetry range.

The final two flights of the series were performed as part of the Galaxia '70 expedition to Parana, Argentina. The first flight on October 22, 1970 had to be terminated less than three hours after launch because of high velocity upper altitude winds. A second launch on November 18, 1970 from the same location resulted in a 13 hour balloon flight. In both flights a malfunction in the on-board pulse height analyzer precluded the accumulation of spectral information. The He\(^3\) counter again operated flawlessly during both flights.

The results presented in the following chapter will be limited to data obtained during the second (Palestine) and third (Ft. Churchill) flights of this series. The results obtained from the first flight have been previously published by Lockwood, St.Onge, Klumpar, and Schow (1969).
During all flights the data is transmitted to a ground receiving station where it is recorded by a seven track video tape recorder operating at 30 ips. The housekeeping data is also periodically monitored and tabulated during each flight in order to judge the overall operation of the system on a real time basis. After each flight the video magnetic tapes are returned to UNH where they are played back into an F.M. subcarrier discriminator and a ground station. The ground station checks each 16 bit data word to verify that the three identification bits are present and to confirm that the parity is correct. Those events which do not contain ID or parity errors are then transferred onto digital tape by an incremental recorder. Each event is identified by an L channel number and a dL channel number and by the relative time of occurrence. The digital tape is processed by the UNH IBM 360 computer which produces an output matrix containing the number of events at each (L, dL) location on the matrix. For convenience each pulse shape-pulse height matrix contains approximately 23 minutes of data, this being the time interval for the data accumulated on each side of a video tape. This accumulation time is sufficient to provide temporal information at least on a broad time scale with a statistical uncertainty of on the order of 2.5 percent on the neutron total counting rate. A final matrix containing all of the spectral data obtained after the instruments reach float altitude is also generated.
CHAPTER VI

RESULTS

The measurements made during the April 3, 1970 and the July 5, 1970 balloon flights are presented in this chapter. The count rate versus time histories for both balloon flights are given in Figures 10 and 11. In each figure the average count rates for each matrix (approximately 23 minutes each) during the flights are presented for the proton recoil, Compton electron, and in-flight calibrator (IFC) events. The constancy of the IFC rate illustrates that no significant gain changes or baseline shifts occurred during either flight or between flights. Furthermore, the fact that the IFC rate does not decrease significantly when the detector passes through the transition maximum (where the neutral and charged particle rates increase by a factor of two to three) indicates that no deadtime correction is necessary. The steady increase in the electron and proton recoil rates after matrix 8 observed on the April 3 flight is attributable to a latitude drift. After launch the balloon drifted in a direction almost normal to contours of equal geomagnetic cutoff moving from 4.6 GV at launch to 2.8 GV at cut-down. The fluxes presented later in this chapter have been corrected for this latitude drift using the latitude curve measured by OGO-6 [Ifedili, 1970].

The data matrices obtained from the matrix program
are shown in Figures 7 and 12. These are 64 x 64 element arrays where each (x,y) element represents the number of counts observed in pulse height channel "L" and pulse shape channel "dL". The data shown in Figure 7 is the sum of all events obtained at float altitude during the July 5th balloon flight and represents an accumulation of 11.0 hours. This matrix is a composite of 29 individual matrices, each representing approximately 23 minutes of data which were individually printed out and carefully checked to insure that no gain changes or baseline drifts had occurred and that the data was of high quality. Figure 12 represents the corresponding float data from the Palestine flight and is an accumulation of 21 individual matrices representing approximately 7.8 hours of data. It should be noted that the data appearing on each matrix is essentially raw data as transmitted from the balloon package. The role of the computer is to read from magnetic tape and print it out in the form most convenient for further analysis. The tracks on each matrix were divided into groups consisting of electron recoils, proton recoils, and IFC events and the total number of events of each type for each pulse height channel was then obtained. The resulting proton recoil and Compton electron histograms are shown in Figures 13 and 14 for the Palestine and Ft. Churchill flights respectively. Note the first few channels rise very sharply in all four histograms. We feel that this is due, in part, to the inability of our PSD to separate alpha particles from protons at low energies and also, in part, to high energy protons which escape from
the scintillator before losing all of their energy. The latter events produce pulses whose shape is indistinguishable from low energy recoil electron pulses. Hence, although these points will be retained in subsequent plots, we will neglect these channels for purposes of calculating fluxes and fitting spectra.

1. Neutrons

The proton energy values and differential widths for each channel were determined from the calibrations as discussed in Appendix B. These are shown in Table B-2. Using these calibrations, a proton recoil spectrum was constructed from the float data for each balloon flight. These are shown in Figures 15 and 16. A reference line obeying a power law of the form $E^{-2.0}$ has been drawn on each figure. To find the atmospheric neutron spectrum, one of the spectral unfolding techniques described in Chapter IV must be used. For this data the technique chosen was the Method of Successive Approximations. The Differentiation Method was also attempted, however, it was found that this technique led to results which contained large oscillations due to the statistical nature of the data. It appears that in order to use the differentiation technique successfully, a large quantity of data with low statistical uncertainty is required. Even then it may be necessary to apply some type of filtering process to smooth the data before this method yields reasonable results.

Using the Method of Successive Approximations, it
was possible to test a large number of input neutron spectra to find those which yielded proton spectra most like that obtained during flight. It was found that the most sensitive comparison could be made by calculating the number of counts expected in each pulse height channel and comparing these by means of a weighted Chi-square test to the raw flight data. The Chi-square is computed from the expression

$$\chi^2 = \sum_i \frac{1}{\sigma_i^2} [y_i - y_0(x_i)]^2$$

where \([y_i - y_0(x_i)]\) is the deviation of the calculated counts per channel from the observed counts per channel for the ith channel and \(\sigma_i^2\) is the variance. In all cases we have assumed that the variance arises only from statistical fluctuations and that our data is described by Poisson statistics. Hence, the variance \(\sigma_i^2\) is just the number of events observed in the ith channel. The values quoted in the discussion below are reduced weighted Chi-square values. If \(\nu\) is the number of degrees of freedom \(\nu = N-n-1\) where \(n\) is the number of constraints, then the reduced Chi-square value is \(\chi^2_\nu = \chi^2/\nu\). Finally, each term of the sum is weighted by the channel width, \(\Delta E_i\), so that the final expression used to determine the reduced weighted Chi-square values quoted below is

$$\chi^2_\nu = \frac{1}{N-n-1} \sum_i \left( \frac{N \Delta E_i}{\sigma_i^2} \left[ y_i - y_0(x_i) \right]^2 \right)$$

Interpretation of the actual Chi-square values obtained is not always clear cut. Generally speaking, the reduced
Chi-square value corresponding to a given number of degrees of freedom is related to the probability that a random choice of the variables would give a larger value of Chi-square [Bevington, 1969]. For example, using a table given by Bevington [1969] with 50 degrees of freedom, a $\chi^2$ of 0.987 gives a probability of 50%, whereas a $\chi^2$ of 1.350 has a probability of only 5% of being exceeded by a random distribution, that is, this, or a smaller value, has a 95% chance of being obtained from a random set of $N$ numbers. Hence, $\chi^2$ values of $1.0 \pm .2$ represent, for the large values of $v$ used here, good fits to the data. The best $\chi^2$ values we obtained were 1.5 and 2.15 for the Ft. Churchill and Palestine balloon flights respectively. At first glance it would appear that these large values do not represent very significant fits to the data. It must be kept in mind that the variance ($\sigma_i^2$) used in computing $\chi^2$ assumed that all uncertainties were statistical. However, in all probability, there are also uncertainties associated with determining the channel widths, the number of events per channel, the cross sections, and any of the many other parameters involved in the calibration which may certainly be as large as or larger than the statistical uncertainties. Hence, it is not unreasonable to assume that the variance was underestimated by a factor of $\nu^2$ which is just the magnitude needed to bring our $\chi^2$ values within the range $1.0 \pm .2$ needed for a significant fit.

As discussed in Chapter IV the unfolding method
employed here does not yield a unique neutron spectrum but rather a set of spectra, each of which are tested against the observed pulse height spectrum with the weighted Chi-square routine. Each trial spectrum consisted of a set of power law functions in energy. Trials were made by assuming various power law functions, characterized by a spectral index \( \gamma \), each covering some fraction of the total energy range of interest. Since a recoil proton may be produced with any energy less than or equal to the incident neutron energy, the neutron sensitivity of this detector is not limited in energy to the finite range of proton energies directly detected. For example, a 50 MeV neutron undergoing an elastic collision with hydrogen in our detector may produce a recoil proton of any energy up to 50 MeV. Hence, our recoil proton distribution is biased by all neutrons whose energy exceeds the threshold level of 3.2 MeV. If the neutron spectrum above 17 MeV (upper limit of direct detection in our detector) falls off steeply (as predicted by Lingenfelter), then the contribution of proton recoils from high energy neutrons will rapidly fall off with increasing neutron energy. In order to determine the atmospheric neutron spectrum then we must consider the effect of the neutron spectrum up through high energies, on the order of 100 MeV.

The spectrum was broken into the following energy intervals: 3-10 MeV, 10-15 MeV, 15-20 MeV, 20-50 MeV, and 50-100 MeV, although the division could be made coarser by
choosing equal spectral indices for any number of successive intervals. Since the detector responds only to proton recoils from 3 to 17 MeV, it is important to realize that the neutron spectrum given above this high energy direct response cutoff (17 MeV) is an inferred spectrum. The sensitivity of the present detector to neutrons above this energy decreases rapidly with increasing neutron energy because of the nature of the proton recoil process. A high energy neutron of energy \( E_n \) has some probability distribution for producing protons of any energy \( E < E_n \) but our detector is sensitive only to those protons produced with energy between 3 and 17 MeV.

In figure 19 are shown the proton recoil pulse height spectra that would be produced by several incident neutron spectra. The pulse height distribution denoted by the open circles is derived from a neutron spectrum of the form \( E^{-1.1} \) over the entire energy range from 1 to 100 MeV. Clearly, this is not a good fit to the measured pulse height spectrum as evidenced by the relative paucity of proton recoils above channel 54 and below channel 20 and the relative overabundance of proton recoils between channels 25 and 45 when compared to the measured distribution. This is an indication that relatively more neutrons are needed above 20 MeV while fewer are needed around 10 MeV and hence the spectrum should be flatter than \( E^{-1.1} \) above 20 MeV and steeper than \( E^{-1.1} \) between 3 and 15 MeV. The dotted line indicates the result of
steepening the neutron spectrum between 1 and 15 MeV to obey an $E^{-1.7}$ dependence. This improves the shape of the pulse height distribution in channels 7-25, but now the calculated pulse height distribution falls much too rapidly above channel 25. This indicates that the chosen neutron spectrum contained too few neutrons at high energy. A third trial, shown as diamonds in Figure 19, shows a definite improvement. Here we have flattened the neutron spectrum between 10 and 50 MeV from the previous choice. Now the fit seems much improved, especially above channel 25, but there is a relative paucity of proton events in channels 7-24. Figure 18 shows two further refinements to the incident neutron spectrum with the final best fit denoted by open circles.

From the foregoing statements, it should be clear that the neutron spectrum above approximately 20 MeV quoted here should be interpreted as no more than an indication of the probable shape of the high energy atmospheric neutron spectrum. It is definitely clear from our measurement that some type of a feature providing a significantly higher flux of neutrons than would be obtained from a spectrum falling as $E^{-1}$ is necessary in the atmospheric neutron distribution above 20 MeV. Using the chosen spectral indices, a proton recoil spectrum was calculated for each assumed neutron spectrum and the expected pulse height distribution was determined. Each calculated distribution was then normalized to the observed count rate distribution.
by finding that multiplier which gave the best weighted Chi-square value when compared with the observation. This multiplier is the spectral constant, $\lambda$, in a power law spectrum of the form $AE^{-\gamma}$. It was found that the best weighted Chi-square values were obtained when the atmospheric neutron spectrum was taken to be flat from 20 to 50 MeV and falling like $E^{-2.0}$ for $E>50$ MeV. This shape is in agreement with the neutron albedo spectrum recently published by Preszler, et al. [1972]. For energies $<20$ MeV, several different combinations were checked. The best fits occurred for spectra which flattened with increasing energy.

For the Ft. Churchill data, the best weighted Chi-square value was 1.5. For this trial the differential neutron spectrum from 3 to 20 MeV is given by

\[
\begin{align*}
0.939 & \times E^{-1.65} & & 3 E \leq 10 \text{ MeV} \\
0.167 & \times E^{-0.90} & & 10 < E \leq 15 \text{ MeV} \\
0.033 & \times E^{-0.30} & & 15 < E \leq 20 \text{ MeV}
\end{align*}
\]

and the extrapolated spectrum above 20 MeV by

\[
\begin{align*}
0.013 & \times E^{0.0} & & 20 \leq E \leq 50 \text{ MeV} \\
33.6 & \times E^{-2.0} & & 50 < E \leq 100 \text{ MeV}
\end{align*}
\]

The predicted pulse height distribution for this spectrum is shown in Figure 17 along with the measured pulse height response.

Similarly for the April 3, 1970 Palestine flight, the best weighted Chi-square value of 2.15 was obtained
for a neutron spectrum described by the following power laws:

\[
\begin{align*}
&0.973 \ E^{-1.80} & &3 \leq E \leq 10 \ MeV \\
&0.123 \ E^{-0.90} & &10 \leq E \leq 15 \ MeV \\
&0.024 \ E^{-0.30} & &15 \leq E \leq 20 \ MeV \\
\end{align*}
\]

between 3 and 20 MeV. The extrapolated spectrum above 20 MeV is given by:

\[
\begin{align*}
&0.0098 \ E^{0.0} & &20 \leq E \leq 50 \ MeV \\
&24.6 \ E^{-2.0} & &50 \leq E \leq 100 \ MeV \\
\end{align*}
\]

The weighted Chi-square value obtained here is somewhat larger than that found for the Ft. Churchill data. This is primarily due to the greater statistical uncertainty inherent in the Palestine data due to shorter flight time. The pulse height distribution expected from this spectrum is shown in Figure 18 as open circles. The solid curve represents the unsmoothed measurement.

The \( \chi^2 \) values quoted in the above discussion were obtained by smoothing the measured pulse height distributions. The smoothed number of counts \( \bar{N}_i \) for the \( i \)th channel is obtained from the expression

\[
\bar{N}_i = \frac{N_{i-1}}{4} + \frac{N_i}{2} + \frac{N_{i+1}}{4}
\]

where \( N_{i-1} \) and \( N_{i+1} \) are the number of counts in the adjacent channels.
The results given above are the measured atmospheric neutron spectra characterized by the latitude, atmospheric depth, and time in solar cycle at which they were measured. To be meaningful with regard to the neutron leakage flux and the high energy proton population in the radiation zones, these must be converted to a neutron leakage spectrum at the top of the atmosphere. Furthermore, to facilitate a meaningful comparison with other measurements and with calculations, these measurements must also be corrected to a standard latitude and to solar minimum. The geomagnetic latitude usually chosen to normalize neutron leakage data is about 40°N, primarily because this is the latitude at which most balloon measurements are conducted. The Pales­tine balloon flight was launched from 42°N geomagnetic latitude, but as mentioned previously, the gondola drifted in geomagnetic latitude necessitating a latitude correction. This correction was made by ascertaining the vertical cutoff rigidity at the position of the gondola at the midpoint of each matrix interval, and reducing the flux for each interval by the amount indicated on the rigidity versus flux curve measured on OGO-6 [Ifedili, 1970]. The latitude drift factor obtained in this manner is 0.837. In order to normalize to solar minimum, the functional dependence of the fast neutron flux as a function of time in the solar cycle must be known at the latitude at which the measurement is made. The cosmic ray intensity is monitored by the count rates observed in ground-based
neutron monitors. It is known that for the Mt. Washington Neutron Monitor, a 25 per cent modulation of the primary cosmic ray intensity is observed over the whole solar cycle. At the time of the Palestine balloon flight, the monitor rate was 85 per cent of its solar minimum rate. Lingenfelter [1963b] has calculated that the 1 to 10 MeV neutron leakage flux varies between .112 neutrons cm\(^{-2}\) sec\(^{-1}\) at solar minimum and 0.091 neutrons cm\(^{-2}\) sec\(^{-1}\) at solar maximum at 40°N geomagnetic latitude. Assuming that the neutron leakage flux varies linearly with the Mt. Washington neutron monitor rate and using linear interpolation, the solar modulation correction factor is found to be 
\[
\frac{0.112}{0.091} = 1.23.
\]
Similarly, for the Ft. Churchill flight, where the Mt. Washington monitor was at 84 per cent and the Lingenfelter 70° neutron leakage fluxes are .465 and .222 neutrons cm\(^{-2}\) sec\(^{-1}\) for solar minimum and solar maximum respectively, we find the solar modulating correction factor to be 
\[
\frac{0.465}{0.3095} = 1.50.
\]
Finally, an altitude correction must be applied in order to obtain the neutron leakage flux at the top of the atmosphere. The precise altitude factor depends upon the anisotropy of the neutron flux and upon the angular response function of the detector. Having no measurement of either, we assume that to first order the neutron intensity at our altitudes (3 to 6 g/cm\(^2\)) is isotropic over the upward hemisphere and that the detector response is isotropic over 4\(\pi\) steradians. Then, using the neutron flux versus altitude curves for specified energy ranges obtained
by Newkirk [1963], we find an altitude correction factor equal to 0.6 ± .1 for neutrons between 1 and 20 MeV. This factor may be used for extrapolating data obtained between 3 and 7 g/cm² to the top with an accuracy of about 20%. The fluxes observed are summarized in Table 3. This table gives the actual measured fluxes and shows the various corrections made to reach the final neutron leakage fluxes and energy spectra at the top of the atmosphere shown in the right hand column.

2. Gamma Rays

Compton electron pulse height histograms due to the interaction of gamma rays in the scintillator are shown in the bottom half of Figures 13 and 14 for the Palestine and Ft. Churchill flights respectively. The broad peak centered about channel 53 in these pulse height distributions represents maximum energy loss events due to relativistic electrons produced by high energy gamma rays as the electrons pass completely through our two inch scintillator.

These electron recoil pulse height distributions have been converted into electron recoil energy spectra by means of the energy and differential energy width calibrations discussed in Appendix B and shown in Table B-3. For the Ft. Churchill flight, the resulting electron recoil spectrum is shown in Figure 20. In order to convert to a differential flux in units of counts/cm² sec MeV, the values shown must be divided by 1.00 x 10⁶ cm² sec. The maximum
TABLE 3. Fluxes and Normalization Constants Obtained for April 3, 1970 and July 5, 1970 Balloon Flights

<table>
<thead>
<tr>
<th>FLIGHT</th>
<th>MEASURED SPECTRUM</th>
<th>MEASURED FLUX 3-10 MEV</th>
<th>MEASURED FLUX 3-100 MEV</th>
<th>ALTITUDE CORRECTION FACTOR</th>
<th>SOLAR CYCLE MODULATION FACTOR</th>
<th>LATITUDE CONVERSION FROM FLUX AT TOP AT SOLAR MINIMUM</th>
<th>LEAKAGE CURRENT AT TOP AT SOLAR MINIMUM</th>
<th>CORRECTED LEAKAGE CURRENT AT TOP AT SOLAR MINIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3-10 MEV</td>
<td>3-100 MEV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/3/70</td>
<td>.024 E^{-0.30}</td>
<td>(.15 E±20 MeV)</td>
<td>.312</td>
<td>.967</td>
<td>0.6</td>
<td>1.13</td>
<td>.837</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>.008 E^0.0</td>
<td>(20 E±50 MeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.6 E^{-2.0}</td>
<td>(50 E±100 MeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/5/70</td>
<td>.033 E^{-0.50}</td>
<td>(.15 E±20 MeV)</td>
<td>.384</td>
<td>1.28</td>
<td>0.6</td>
<td>1.50</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>.0134 E^0.0</td>
<td>(20 E±50 MeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>33.6 E^{-2.0}</td>
<td>(50 E±100 MeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

64
energy loss peak occurs at 7.6 MeV which is within 200 keV of its expected position based upon a minimum ionization of 1.96 MeV/g cm\(^{-2}\). This provides added confidence that our energy calibration is accurate at high energies. Fitting a power law function of the form \(E^{-\gamma}\) to this spectrum gives a spectral index, \(\gamma\), of 1.5.

The electron recoil energy spectrum for the April 3rd Palestine flight is shown in Figure 21. To convert this spectrum to a differential flux, the values must be divided by \(7.08 \times 10^5\) cm\(^2\) sec. This spectrum is nearly identical to the previous spectrum taken at higher latitude but is somewhat softer, having a spectral index of 1.6.

These electron recoil spectra have been unfolded using the technique described in Chapter IV to obtain the gamma ray spectrum incident on the detector. As previously mentioned, any spectral unfolding process is most difficult and subject to large errors. In this regard, the atmospheric gamma ray energy spectra obtained in this experiment should be considered as preliminary. The most accurate determination would require an extensive set of measured response functions from monoenergetic gamma rays which can only be obtained from nuclear reactions on a high energy accelerator.

The unfolding technique previously described yields an electron recoil spectrum for a chosen incident gamma ray spectrum. In Figure 22 we show the electron recoil spectrum obtained at float during the Palestine balloon flight as
closed circles. The line represents the electron recoil spectrum obtained by an incident gamma ray spectrum given by $0.82 \times E^{-2.2}$ for $1 < E < 4$ MeV and by $0.357 \times E^{-1.6}$ for $4 < E < 30$ MeV. Similarly, the Ft. Churchill spectrum is shown in Figure 23. The solid line is the electron recoil spectrum from an incident gamma ray spectrum given by $1.05 \times E^{-2.2}$ for $1 < E < 4$ MeV and by $0.398 \times E^{-1.5}$ for $4 < E < 30$ MeV. The break in the spectrum occurring at 4 MeV is necessary to account for the steepening of the electron recoil spectrum below 2.5 MeV. The exact placement of this spectral feature in the atmospheric gamma ray spectrum is to within ±1 MeV. Furthermore, the detailed shape of this feature cannot be unambiguously determined from this data. A trial spectrum containing a triangular shaped "peak" in the gamma ray spectrum between 4 and 5 MeV was also tested. This spectrum did not yield as good a fit to the data as the above mentioned spectra.

These results will be discussed in light of other atmospheric gamma ray measurements in the following chapter.
CHAPTER VII

DISCUSSION AND CONCLUSIONS

1. Neutrons

In order to discuss the results presented in the previous chapter in light of other measurements and calculations of the neutron leakage flux, it is necessary to make absolutely clear what quantity is being discussed. That there is a distinction between the terms neutron leakage rate, current, and vertical flux on the one hand and omnidirectional flux on the other hand must be clear. Any omnidirectional detector which makes a measurement of fast neutrons at some point within the atmosphere measures the omnidirectional intensity or flux. However, a similar detector at or above the top of the atmosphere or an instrument having finite angular resolution measuring the fast neutron environment either above or within the atmosphere is capable of measuring the neutron leakage current or vertical flux. The quantity of interest with respect to the CRAND radiation belt source theory is the leakage current. This is the quantity which was calculated by Lingenfelter [1963b]. The neutron leakage current is given by

\[ i(t) = \int_0^{2\pi} \int_0^{\pi/2} \phi(\theta) \cos \theta \sin \theta \, d\theta \, d\phi \]
where $\phi(\theta)$ is the unidirectional differential intensity (neutrons/cm$^2$ sec MeV sr), $\theta$ is the zenith angle, and cylindrical symmetry about the zenith is assumed. Note that integration is only over the upper hemisphere since it is the upward moving neutrons which are of interest. This same quantity has been termed current [Lingenfelter, 1963b], neutron leakage rate [Lockwood, 1972], and vertical flux [White, et al., 1972]. If, however, one calculates the quantity

$$
\int_{0}^{2\pi} \int_{0}^{\pi/2} \phi(\theta) \sin \theta d\theta d\phi
$$

then this is the omnidirectional flux passing through a hemisphere. This is the quantity reported by Preszler, et al. [1972], Holt, et al. [1966], and Mendell [1971], and computed by Armstrong and Chandler [1972]. Since the leakage current is the quantity of interest with regard to CRAND, it will be used exclusively in the following discussion.

Note this requires that in the case where a measurement is made within the atmosphere using an omnidirectional detector, one must assume some type of angular distribution for the incident neutrons. If the distribution is assumed to be isotropic over the upper hemisphere, i.e., $\phi(\theta) = K$, a constant, then the neutron leakage current obtained will just be 0.5 times the omnidirectional flux. If, however, one assumes an angular distribution which is peaked toward the vertical, for example, $\phi(\theta) = K \cos^2 \theta$, then the neutron
leakage current is 0.75 times the omnidirectional flux. For lack of any strong evidence to the contrary, we will assume that angular distribution which gives the lowest neutron leakage, namely, the isotropic distribution.

The neutron leakage current as calculated by various investigators is shown in Figure 1. The higher energy measurements reported by White, et al. [1972] and by Heidbreder, et al. [1970] are also shown for comparison. The latter spectrum for neutrons greater than 100 MeV is that reported by them for upward moving neutrons observed at 7 g/cm² at 42°N geomagnetic latitude. The spectral shape is based upon a total of 17 events which gave double elastic scattering on hydrogen and hence were uniquely identifiable as to energy and direction in their spark chamber. Of these events, only ten were upward moving. Their reported absolute flux is based upon these ten events. The calculations of Lingenfelter [1963], Newkirk [1963], and Wilson, et al. [1969] were discussed in Chapter 2. The spectrum taken from Freden and White [1962] is the predicted neutron flux calculated from the measured intensity of radiation belt protons and CRAND theory. It is the neutron leakage flux needed to explain the measured proton intensities assuming cosmic ray albedo neutron decay is the sole source of these protons and assuming atmospheric loss by ionization and nuclear interactions. The magnitude has been increased by a factor of 7 to include the injection coefficient that they omitted [White, et al., 1972]. The staircase spectrum of Armstrong
and Chandler [1972] is the result of a Monte Carlo calculation computed from nuclear interaction cross sections and assuming protons and alpha particles incident on the top of the atmosphere to initiate the nucleonic cascade.

Measurements of the neutron leakage spectra in the energy range 1 to 100 MeV are shown in Figure 24. These are all given in terms of the leakage current at the top of the atmosphere at a geomagnetic latitude of 40°N at solar minimum. The calculation by Lingenfelter [1963b] and the measurement of White, et al. [1972] have been reproduced from Figure 1 for reference. The spectrum of Jenkins, et al. [1971] was measured on the OGO-6 satellite. The spectrum shown was derived from their high latitude result and has been reduced to 50 km altitude and has a spectral shape given by $E^{-1.0}$, the largest spectral index consistent with their published range of values. The spectrum measured by Baird and Wilson [1966] is taken from their reported rocket measurement at solar minimum and at the top of the atmosphere. Hence, the only correction applied before plotting on this figure is a reduction by a factor of 4.15 due to the latitude dependence. Since this measurement was made at the top of the atmosphere, it is already a neutron leakage current.

The spectrum measured by White, et al. [1972] was made on a balloon flight to 4.6 g/cm² at 40°N geomagnetic latitude in September, 1971 with a directional detector. They were able to measure the angular distribution of
atmospheric neutrons with an angular resolution of 10° at angles of 20° to 70° to the vertical at energies from 12.5 to 90 MeV. They report a tendency for upward moving neutrons to have an intensity distribution which is peaked toward the vertical at low energies. Furthermore, they find the number of downward moving neutrons to be about one-third of the upward moving ones at their altitude (4.6 g/cm²). To find the vertical flux, they extrapolated to 0° and 90°, multiplied by cosθ and integrated over solid angle. Their result is shown as solid circles in Figure 24. No altitude, latitude, or solar cycle corrections were necessary in plotting this result on the figure. Note that their spectrum is almost flat between 15 and approximately 50 MeV, and then falls approximately as E⁻² above this energy. This is just the type of feature which, as pointed out in the previous chapter, is necessary to explain our observed pulse height distribution. In fact, our best weighted Chi-square values are obtained for an extrapolated neutron spectrum which is flat between 20 and 50 MeV and falls as E⁻² above 50 MeV.

Three other sets of data are shown on this figure for the 1 to 10 MeV energy region. All three of these measurements Holt, et al. [1966], Mendell [1971], Albernhe and Talon [1969], and Haymes [1964] were made with balloon-borne omnidirectional scintillation detectors. Each has been normalized to 40°N geomagnetic latitude and to solar minimum and extrapolated to the top of the atmosphere using the same technique as described in Chapter VI for
Previous estimates [Hess and Killeen, 1966; Dragt et al. 1966; Farley et al., 1970; Farley and Walt, 1971] on the ability of cosmic ray neutron albedo decay to account for the observed fluxes of trapped high energy protons in the inner radiation zone have concluded that this source alone is inadequate. For example, Dragt et al. [1966] conclude that trapped radiation belt protons with energies $E > 20$ MeV can be explained by CRAND injection only if uncertainties in the mean atmosphere and the neutron source work in such a direction to increase the flux by a factor of 50 over what they calculate. Furthermore, they conclude that below 20 MeV there are too many protons to be accounted for by neutron decay injection and some other source is needed. Hess and Killeen [1966] consider the same problem, using a somewhat different atmospheric density model which has a factor of ten greater high-altitude electron density than the model used by Dragt. They point out that the atmospheric density at 2000 - 3000 km is not well known and that it is impossible to choose between either of the two atmospheric models. Hess and Killeen believe that at high altitude the flux they calculate is close enough to the measured flux to say that the trapped protons in the middle of the inner belt may well come from galactic cosmic ray neutrons. At low altitude they conclude that some other mechanism must be operative.

Farley et al. [1970] and Farley and Walt [1971] have gone one step further with the inclusion of inward radial
diffusion as an additional source of inner zone protons with energies between 20 and 170 MeV. They conclude that diffusion of outer zone protons at the geomagnetic equator is a sufficient source from $L = 1.3$ to $L = 1.7$ to make up the deficiencies apparent from using neutron leakage decay as the sole source. They point out that important discrepancies remain below $L = 1.3$. Furthermore, their calculation was not extended to regions off the equatorial plane nor did it include the possible effects of pitch angle diffusion.

Without exception, all of the above calculations have used as a neutron leakage spectrum that determined by Lingenfelter [1963b]. The results on the neutron leakage spectrum reported here, as well as other recent measurements and calculations, indicate that the Lingenfelter neutron leakage spectrum is deficient in neutrons by a factor of five at 10 MeV and increasing to a factor of about 40 at 50 MeV. It is clear that the neutron leakage source of high energy protons in the radiation belt should now be reevaluated in light of these most recent results.

The results given in the previous chapter were stated with no indication of their absolute uncertainty. It is not an easy task with a spectral measurement of this kind to set meaningful limits on either the accuracy or the precision of the derived spectrum. Statistical uncertainties may be determined from the number of counts obtained. Approximately 450 proton recoil counts were obtained in each channel during the float portion of the
Palestine flight, giving a statistical uncertainty of about 5% for any one channel. During the Ft. Churchill flight, we obtained approximately 700 counts per channel, yielding a statistical uncertainty of about 4% per channel. In addition to these ever present statistical uncertainties, there may be several other sources of uncertainty in our experiment. For example, the unfortunate choice of a non-linear pulse height analyzer in the flight package has made determination of the differential channel widths much more difficult. The width of any one channel may be uncertain to ±20%. Uncertainties in the number of events in each channel which may arise due to improper identification of a proton recoil event (i.e., ambiguities in pulse shape discrimination) are probably no greater than 5 to 10 per cent in the worst case (small pulse heights).
2. Gamma Rays

Intercomparison of reported results on the atmospheric gamma ray spectrum is made difficult by the failure of most investigators to unfold their measured energy spectra. Most measurements of the atmospheric photon spectrum have been made at energies below the threshold of the present detector. Of the measurements made in the 1-10 MeV range, most are done with inorganic NaI or CsI scintillation detectors and the results are presented as an energy loss spectrum in the respective detectors. At higher energies there are an increasing number of results being reported from spark chambers and Cerenkov telescopes, but these are primarily directional measurements of the vertically incident cosmic ray photons and hence cannot be directly compared to our result.

Figure 2 shows the present situation regarding the atmospheric photon spectrum from ~100 keV to >100 MeV. The dashed line is the calculation by Puskin [1970] and was discussed in Chapter II. The three solid circles are high energy measurements reported by Fichtel, et al. [1969] using a digitized spark chamber. They measured the angular distribution of atmospheric gamma rays and found a zenith angle dependence for energies greater than 100 MeV which could be described by a sec $\theta$. The points shown in the figure are their gamma ray intensities at 3 g/cm$^2$ integrated over all solid angles. Their intensity is somewhat larger than the straight line extrapolation from lower
energy results. This they attribute to the expected enhancement of the gamma ray flux in this energy region due to the decay of neutral pions produced by cosmic rays in the atmosphere. The staircase spectrum of Peterson, et al. [1972] is measured at 3 g/cm² and 40°N latitude with a three inch by three inch NaI scintillation detector. This is a count rate spectrum and has not been unfolded for their detector response. They report a slight steepening of the atmospheric gamma ray spectrum in the 1-3 MeV range similar to what has been found in the present experiment. They state that this might be due "to build-up effects within a gamma ray mean-free path from zero depth" on to the diffuse component of the cosmic gamma ray flux. Helmken and Hoffman [1971] using a gas Cerenkov detector measured the atmospheric gamma ray flux at 5.2 mb over Palestine, Texas in September, 1970. They report a flux of gamma rays greater than 15 MeV of (8.9 ± 0.9) x 10⁻³ cm⁻² sec⁻¹ sr⁻¹. Taking an isotropic distribution and assuming that a power law of the form E⁻¹.6 is a suitable representation of the atmospheric gamma ray spectrum above 15 MeV then we obtain the curve marked 3 on Figure 2. This is in excellent agreement with an extrapolation of our results at lower energy denoted as curve 4 on the same figure. Integrating our spectrum from 1-10 MeV, we obtain fluxes of 0.66 photons/cm² sec at float altitude for the Palestine flight (curve 4, Figure 2) and 0.86 photons/cm² sec for the Ft. Churchill flight.
3. Conclusions

In summary, we have used a liquid scintillation detector employing pulse shape discrimination to measure the flux and energy spectrum of fast neutrons ($E > 3$ MeV) and gamma rays ($1 \leq E \leq 10$ MeV) near the top of the atmosphere. The omnidirectional, differential, atmospheric neutron spectrum from 3-20 MeV at 3.5 g/cm² over Palestine, Texas ($\lambda = 42°N$) on April 3, 1970 can be described by a spectrum of the form $0.973 \ E^{-1.8} \ (3 \leq E \leq 10 \ MeV)$, $0.123 \ E^{-0.9} \ (10 \leq E \leq 15 \ MeV)$, $0.024 \ E^{-0.3} \ (15 \leq E \leq 20 \ MeV)$. The spectrum above 20 MeV as inferred from our data may be described by $0.0098 \ E^{0.0} \ (20 \leq E \leq 50 \ MeV)$, $24.6 \ E^{-2.0} \ (50 \leq E \leq 100 \ MeV)$ neutrons/cm²sec MeV over the indicated energy ranges. To convert to a neutron leakage current at the top of the atmosphere at $\lambda = 40°N$ at solar minimum, the constants must be multiplied by the factor 0.284. The leakage flux obtained in this manner is 0.089 neutrons/cm²sec between 3 and 10 MeV and 0.27 neutrons/cm²sec between 3 and 100 MeV. For the balloon flight from Ft. Churchill, Canada ($\lambda = 68°N$) at an altitude of 6 g/cm², the measured neutron spectrum between 3 and 20 MeV is given by $0.939 \ E^{-1.65} \ (3 \leq E \leq 10 \ MeV)$, $0.167 \ E^{-0.9} \ (10 \leq E \leq 15 \ MeV)$, $0.033 \ E^{-0.3} \ (15 \leq E \leq 20 \ MeV)$, and the inferred spectrum above 20 MeV by $0.0134 \ E^{0.0} \ (20 \leq E \leq 50 \ MeV)$, $33.6 \ E^{-2.0} \ (50 \leq E \leq 100 \ MeV)$ neutrons/cm²sec MeV over the indicated energy intervals. Correcting to the top of the atmosphere at solar minimum and converting to a neutron leakage current (total multiplicative
factor = 0.45), we obtain a leakage flux of 0.173 neutrons/cm²sec between 3 and 10 MeV and 0.58 neutrons/cm²sec between 3 and 100 MeV.

We have found no evidence for the existence of spectral features in the atmospheric neutron spectrum due to nuclear resonance absorption by atmospheric nitrogen and oxygen below 10 MeV.

The neutron leakage spectrum reported here indicates that Cosmic Ray Albedo Neutron Decay may be a sufficient source to account for the observed intensities of high energy protons in the radiation zones. As discussed earlier in this chapter, all previous calculations of the CRAND source theory, which were based upon the neutron leakage currents given by Lingenfelter [1963b], must now be re-evaluated in light of these new results.

The atmospheric gamma ray spectrum has been measured between 1 and 10 MeV and is described by a double power law function over this range of the form 0.82 $E^{-2.2}$ (1≤$E$≤4 MeV), and 0.357 $E^{-1.6}$ (4≤$E$≤10 MeV) photons/cm²sec MeV at 3.5 g/cm² during the balloon flight from Palestine, Texas and by 1.05 $E^{-2.2}$ (1≤$E$≤4 MeV) and 0.398 $E^{-1.5}$ (4≤$E$≤10 MeV) photons/cm²sec MeV at 6 g/cm² during the Ft. Churchill flight. The measured flux in the energy range from 1 to 10 MeV was found to be 0.66 photons/cm²sec for the Palestine flight and 0.86 photons/cm²sec for the Ft. Churchill flight.
CHAPTER VIII

RECOMMENDATIONS FOR FUTURE EFFORTS

Based on the requirements for measurements of the atmospheric neutron spectrum as enumerated in the introduction to this thesis, the following recommendations for future work stand out above all others. Namely, the need to develop a neutron detector having moderate directional resolution which is efficient for the detection of fast neutrons up to 100 MeV with the capability of resolving structure in the energy distribution. Such a detector should ideally have the ability to determine the direction of arrival of an incident neutron to within 10 degrees, but even the ability to distinguish between upward moving and downward moving neutrons would be a step in the proper direction. High efficiency is important in obtaining the best possible statistics. Because of the relatively low flux of fast neutrons and the necessity of obtaining a large number of events in order to determine the energy spectrum accurately, a large detector is required. Furthermore, the dynamic range of the system should be large enough so that low energy limit of detection is well within the range of common laboratory neutron and gamma ray calibration sources. This is necessary in order to constantly monitor the calibration of the system.

Further experimentation is needed to delineate the operating characteristics of the organic scintillator
at high neutron energies (20 to 100 MeV). Neutron-carbon interactions within the scintillator might provide a means of measuring the energy spectrum of fast neutrons up to energies ~100 MeV. To this author's knowledge, there has been no experimental work published regarding the ability of a pulse shape discriminated organic scintillator to separate particles of mass greater than three. A detector with such properties might find application in the detection of the nucleonic component of the cosmic rays.
BIBLIOGRAPHY


Hopkins, J. C., The $^1\text{H}(n,n)^1\text{H}$ Scattering Observables Required for High-Precision Fast Neutron Measurements, Nuclear Data Tables A-9, 137 (1971).


Jesson, P., M. Bormann, F. Dreyer, H. Neuert, Experimental Excitation Functions for (n,p), (n,t), (n,α), (n,2n), (n,ρ), and (n,α) Reactions, Nuclear Data Tables A-1, 103 (1965).


Owen, R. B., Pulse Shape Discrimination Identifies Particle Types, Nucleonics 17, 92 (1959).

Peterson, L. E., D. A. Schwartz, and J. C. Ling, Spectrum of Atmospheric Gamma Rays to 10 MeV at $\lambda = 40^\circ$, to be published, 1972.


St. Onge, R. N. and J. A. Lockwood, A Total Enclosing Active Charged Particle Shield, Nuc. Instr. and Meth. 69, 347 (1969b).


APPENDIX A

RECOIL PROTON ENERGY DISTRIBUTION

In Chapter IV of the text it was stated that if the n-p scattering cross section is isotropic in the center of mass system, then it can be shown that the energy distribution of recoil protons is a rectangular distribution, even though the scattering cross section in the laboratory system of the detector is not isotropic. In this appendix we give the proof of this important relationship. Furthermore, the derivation is generalized to yield the proton distribution for the case where the center of mass cross section is anisotropic.

Let us first determine the relationship between the laboratory, \( \sigma_{\text{lab}}(\theta_{\text{lab}}) \), and center of mass, \( \sigma_{\text{cm}}(\theta_{\text{cm}}) \), differential cross sections. In general, this relationship is given by [Schiff, 1968]

\[
\sigma_{\text{cm}}(\theta_{\text{cm}}) = \frac{M_2(M^2_2-M^2_1\sin^2\theta_{\text{lab}})^{1/2}}{[M_1\cos\theta_{\text{lab}}+(M^2_2-M^2_1\sin^2\theta_{\text{lab}})^{1/2}]^2} \sigma_{\text{lab}}(\theta_{\text{lab}}) \tag{A-1}
\]

or

\[
\sigma_{\text{lab}}(\theta_{\text{lab}}) = \frac{[M_1\cos\theta_{\text{lab}}+(M^2_2-M^2_1\sin^2\theta_{\text{lab}})^{1/2}]^2}{M_2(M^2_2-M^2_1\sin^2\theta_{\text{lab}})^{1/2}} \sigma_{\text{cm}}(\theta_{\text{cm}}) \tag{A-2}
\]

which gives the differential cross section in the laboratory in terms of the laboratory scattering angles, the
masses $M_1$ and $M_2$ of the incident and target particles and the center of mass cross section. Now for the special case of neutron – proton scattering $M_1 = M_2 = M$, hence, equation A-2 becomes

$$\sigma_{lab}(\theta_{lab}) = 4(\cos \theta_{lab}) \sigma_{cm}(\theta_{cm})$$  \hspace{1cm} A-3

or writing the cross sections as differentials

$$\frac{d\sigma_{lab}}{d\Omega_{lab}} = 4 \cos \theta_{lab} \frac{d\sigma_{cm}}{d\Omega_{cm}}$$  \hspace{1cm} A-4

But $\frac{d\sigma_{lab}}{d\Omega_{lab}} = \frac{d\sigma_{lab}}{d\theta_{lab}} \frac{d\theta_{lab}}{d\Omega_{lab}}$ and $d\Omega_{lab} = 2\pi \sin \theta_{lab} d\theta_{lab}$

Thus solving for $d\sigma_{lab}/d\theta_{lab}$ we have

$$\frac{d\sigma_{lab}}{d\theta_{lab}} = 2\pi \sin \theta_{lab} \frac{d\sigma_{lab}}{d\Omega_{lab}}$$  \hspace{1cm} A-5

or using equation A-4

$$\frac{d\sigma_{lab}}{d\theta_{lab}} = 8\pi \sin \theta_{lab} \cos \theta_{lab} \frac{d\sigma_{cm}}{d\Omega_{cm}}$$  \hspace{1cm} A-6

From the kinematics of the reaction it can be demonstrated that

$$E_p = E_n \sin^2 \theta_{lab}$$  \hspace{1cm} A-7

where $E_n$ is the incident neutron energy. Differentiation with respect to $\theta_{lab}$ gives
Rewriting the left hand side of equation A-6:

\[ \frac{dE_p}{d\theta_{lab}} = 2E_n \sin \theta_{lab} \cos \theta_{lab} \]  

Hence, combining A-6, A-8, and A-9 we have finally

\[ \frac{d\sigma_{lab}}{dE_p} \frac{d\sigma_{lab}}{dE_p} = \frac{d\sigma_{lab}}{dE_p} \frac{d\sigma_{lab}}{dE_p} \]

This result gives the general relationship between the proton energy distribution and the center of mass differential cross section. One can see that if \( \frac{d\sigma_{cm}}{d\theta_{cm}} \) is isotropic then \( \frac{d\sigma_{cm}}{d\theta_{cm}} = \Lambda \), a constant and the total cross section \( \sigma \) is just

\[ \sigma = 4\pi \Lambda \]

so

\[ \frac{d\sigma_{lab}}{dE_p} = 4\pi \Lambda = \frac{\sigma}{E_n} \]

which is a constant, independent of recoil proton energy. Hence, the proton recoil energy distribution produced by monoenergetic incident neutrons of energy \( E_n \) is constant for all proton energies up to \( E_p = E_n \).
APPENDIX B

DETECTOR CALIBRATIONS

In order to accurately measure the atmospheric neutron spectrum, the detector described in the main body of this thesis is calibrated with a series of monoenergetic gamma ray sources immediately before each balloon flight. Further, before shipment to the launch site, the detector is also calibrated with 14 MeV neutrons from the \( T(d,n)He^4 \) reaction on the UNH 400 keV Van de Graff accelerator. These calibrations are made such that each pulse height spectrum is obtained simultaneously on both the nonlinear on-board pulse height analyzer and a TMC Model 401D laboratory pulse height analyzer. This allows for comparison of the position of the Compton edges on each system and makes it possible to calibrate the flight pulse height analyzer against a linear laboratory analyzer. A set of pulse height distributions from the laboratory pha are shown in Figures 25a-d for Na\(^{22}\), Co\(^{60}\), Th\(^{228}\), and AmBe respectively. A summary of all calibrations from March 1969 until the present is given in Table B-1.

A further set of neutron calibrations were made during February, 1972 using the 5.5 MeV Van de Graff accelerator at the Lowell Technological Institute, Lowell, Massachusetts. Protons were accelerated onto a tritium target and the reaction \( T(p,n)He^3 \) was used to obtain
monoenergetic neutrons at six energies in the range from 3.473 to 4.726 MeV by varying the incident beam energy. Time of flight was used to decrease the background from gamma rays and scattered neutrons. This was accomplished by using the accelerator in a pulsed beam mode and setting a narrow timing window to gate the detector to accept only those neutrons whose arrival times corresponded to the travel times of the neutron energy of interest. Calibration points were obtained at six distinct energies during this calibration. Figure 26 shows the proton recoil spectra obtained from the on-board pulse height analyzer. The neutron energy as well as the channel number corresponding to the half-maximum are shown for each curve. Note each successive curve is shown displaced to the right by 5 channels to avoid confusion. From this set of curves and an additional calibration at $E = 14.1$ MeV from the $T(d,n)He^4$ reaction, a plot of neutron energy versus flight channel number was constructed (Figure 27). This serves as the energy calibration for the detector system. In addition, the differential flight channel widths are needed to obtain the number of proton recoils per unit energy. These are found by reading the neutron energy at the center of each channel from the previous figure, and subtracting successive values. These are then plotted and fitted by a smooth curve. The values of $\Delta E_n$ read from this smooth curve (Figure 28) are then the differential channel widths used to convert the number of counts obtained in each channel
to protons per MeV at the energy corresponding to the center of the channel. Table B-2 shows the energies and energy widths for each channel obtained as described above.

Gamma ray calibrations made at the same time with both the flight and a laboratory pulse height analyzer make it possible to construct a plot of maximum Compton electron energy against laboratory pha channel number. This curve is shown in Figure 29. Furthermore, four of the neutron calibrations at Lowell were also obtained on the laboratory pha. The four half height edges at the maximum proton recoil energy determined from this data may be used along with the Compton energy calibration of the previous figure to provide the relationship between electron and proton energy for equal pulse heights at four points. These are plotted as the lower four points in Figure 3.

Since the energy threshold of the flight system is somewhat above the Co$^{60}$ Compton edge, only the two highest energy gamma ray sources Th$^{228}$ and Am-Be give full Compton edge spectra on matrices. These two Compton energies do, however, provide two more data points on Figure 3. These points are obtained by direct comparison of the neutron energy versus flight channel number curve in Figure 27 with the flight channel numbers obtained for the Th$^{228}$ and Am-Be Compton edges. Figure 3 also contains the pulse height response for NE-213 as determined by other investigators. Using these results as a guide and the six direct calibration points, we have constructed the pulse height
response curve shown as the heavy line and given by

\[ E_e = 0.220 E_p^{1.410} \]

In order to determine this relationship directly, a large number of calibration points are needed over a wide range of gamma ray and neutron energies. The neutron calibrations must be made at an accelerator facility where a wide range of targets and beam energies are available. We believe the pulse height response determined above is accurate to within 10 per cent based on the variations reported by other investigators.

Using this pulse height response relationship and the previously determined neutron energy versus channel number curve, we obtain the Compton electron energy calibration given in Table B-3.

From the calibration summary in Table B-1, one can see that gain shifts of up to ~5 channels occurred during the calibration history of the detector. In particular, the locations of the calibration peaks determined at Lowell Technological Institute on February 4, 1972 indicate the gain was depressed from its value during the 1970 balloon flights. It was necessary to correct for this shift when applying the calibration to the data obtained during the balloon flights.
TABLE B-1: Calibration Summary. The table gives the L flight channel number at which the peak in the count rate distribution occurs for each source listed.

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<th>Date</th>
<th>Source</th>
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<th>(D,T) neutrons</th>
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<th>IFC Peak 2</th>
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*Balloon Flight
TABLE B-2: Proton energy and energy width calibration for each L channel (1-63) of the flight pulse height analyzer.

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TABLE B-3: Electron energy and energy width calibration for each L channel (1-63) of the flight pulse height analyzer. Determined from $E_e = 0.220 \ E_p^{1.410}$

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FIGURE CAPTIONS

Figure 1: A summary of recent experimental results and calculations of the Earth's albedo neutron leakage spectrum. All data and calculations refer to 40°N geomagnetic latitude.

Figure 2: A summary of experimental results and calculations of the atmospheric gamma ray spectrum. Experimental measurements are energy loss spectra given in units of counts cm⁻²sec⁻¹MeV⁻¹. Theoretical calculations are true photon spectra.

Figure 3: Electron energy versus proton energy pulse height response curves for NE-213. The curves indicate the proton recoil energy required to produce a pulse in NE-213 whose amplitude is equal to that produced by an electron of the prescribed energy.

Figure 4: Idealized proton recoil spectra produced by monoenergetic neutrons of low (Curve B), intermediate (Curve A), and high energy (Curve C).

Figure 5: Total cross sections for n-hydrogen and n-carbon interactions from 1 to 300 MeV.

Figure 6: Absorption Probability. The curves indicate the number of neutrons cm⁻²sec⁻¹MeV⁻¹ which are absorbed in the scintillator as a function of energy for an incident neutron spectrum of the form N₀(E) 1.0 E⁻².0 neutrons cm⁻²sec⁻¹MeV⁻¹.

Figure 7: Raw data matrix obtained during 11 hours at float over Ft. Churchill, Manitoba, Canada on July 5, 1970. Electron events due to gamma rays (marked "e") are clearly distinguishable from proton recoils ("p") due to neutrons. The events marked "a" and "3a" are tentative identifications of events believed to arise from the interaction of high energy neutrons with carbon. IFC denotes the in-flight calibration source.

Figure 8: Block diagram of the total detector system.

Figure 9: Balloon flight train for the April 3, 1970 balloon flight from Palestine, Texas.
Figure 10: Count rate versus time for Palestine balloon flight. The balloon reached float altitude at 1520 GMT during matrix 8. The increase in count rate prior to this time is due to altitude variations. After 1520 GMT the balloon floated at a mean altitude of 4 g/cm² to within ± .5 g/cm².

Figure 11: Count rate versus time for the Ft. Churchill flight. The instrument reached float altitude at 1204 GMT during matrix 7. The altitude as recorded by an on-board photobarograph drifted slowly from an initial altitude of 4.2 g/cm² to 6.0 g/cm² at cutdown. The large increase in count rate prior to 1204 GMT is due to passage through the transition maximum.

Figure 12: Raw data matrix obtained during 7.8 hours at float after launch from Palestine, Texas on April 3, 1970.

Figure 13: Proton recoil and Compton electron histograms for Palestine balloon flight at float altitude.

Figure 14: Proton recoil and Compton electron histograms for Ft. Churchill balloon flight at float altitude.

Figure 15: Proton recoil energy spectrum for Palestine balloon flight.

Figure 16: Proton recoil energy spectrum for Ft. Churchill balloon flight.

Figure 17: Pulse height recoil proton distributions for the Ft. Churchill balloon flight. The solid curve shows the counts per channel observed during the flight and the dotted distribution is that predicted by an atmospheric neutron spectrum of the form $A_1 E^{-\gamma_1}$ where $\gamma = 1.65$ for $1 \leq E < 10$ MeV, 0.9 for $10 \leq E < 15$ MeV, 0.3 for $15 \leq E < 20$ MeV, 0.0 for $20 \leq E < 50$ MeV, and 2.0 for $E > 50$ MeV. This is the best fit found for the Ft. Churchill balloon flight. $A_1$ is the neutron intensity at 1 MeV.

Figure 18: Pulse height recoil proton distribution from the Palestine balloon flight. The solid curve shows the counts per channel observed during the flight and the distribution shown by the open circles is that predicted by an atmospheric spectrum of the form $A_1 E^{-\gamma_1}$ where $\gamma = 1.80$ for $1 \leq E < 10$ MeV, 0.9 for $10 \leq E < 15$ MeV, 0.3 for $15 \leq E < 20$ MeV, 0.0 for $20 \leq E < 50$ MeV, and 2.0 for $E > 50$ MeV. This is the best fit observed for the Palestine balloon flight. The dotted curve is that obtained by a spectrum with a slightly flatter spectrum between 1 and 10 MeV and does not agree as well with the measurement as
shown by the reduced Chi-square values. In both cases, $A_i$ is the neutron intensity at 1 MeV.

**Figure 19:** Several trial spectra shown in comparison with the measured Palestine pulse height distribution.

**Figure 20:** Electron recoil energy spectrum for July 5, 1970 Ft. Churchill balloon flight at a flight altitude corresponding to 6 g/cm$^2$ of atmosphere above the instrument. To find the differential flux in counts/cm$^2$sec MeV, divide by $1.00 \times 10^6$cm$^2$sec.

**Figure 21:** Electron recoil energy spectrum for April 3, 1970 Palestine balloon flight. Float altitude equals 3.5 g/cm$^2$ residual atmosphere. To find the differential flux in counts/cm$^2$sec MeV, divide by $7.08 \times 10^5$cm$^2$sec.

**Figure 22:** Figure 21 redrawn in terms of a differential flux. The solid line represents the electron recoil spectrum calculated from an incident gamma ray spectrum given by $0.82 E^{-2.2}$ for $1 \leq E \leq 4$ MeV and $0.357 E^{-1.6}$ for $4 \leq E \leq 30$ MeV.

**Figure 23:** Figure 20 redrawn in terms of a differential flux. The solid line represents the electron recoil spectrum calculated from an incident gamma ray spectrum given by $1.05 E^{-2.2}$ for $1 \leq E \leq 4$ MeV and $0.398 E^{-1.6}$ for $4 \leq E \leq 30$ MeV.

**Figure 24:** The neutron leakage spectrum at 40°N geomagnetic latitude at solar minimum. All spectra shown are measured except for the Lingenfelter calculation.

**Figure 25a:** Pulse height spectrum from Na$^{22}$ source. The numbers refer to the channel number at 3/4 of the Compton edge.

**Figure 25b:** Pulse height spectrum from Co$^{60}$ source. The channel numbers corresponding to 3/4 points on the Compton edge for the 1.17 MeV and 1.33 MeV gamma ray lines are shown.

**Figure 25c:** Pulse height spectrum from Th$^{228}$ source. Channel 75 corresponds to 3/4 maximum of the Compton edge height. The two peaks from the in-flight calibrator are also shown centered on channels 103 and 131.

**Figure 25d:** Pulse height spectrum from Am-Be source with background subtracted away. Channel 114 is the 3/4 Compton edge from 4.43 MeV gamma rays.
Figure 26: Proton recoil spectra from six different energies from the $H^3(p,n)He^3$ reaction. The neutron energies and the channel numbers at half maximum are shown for each case. Each spectrum is displaced 5 channels to the right for clarity.

Figure 27: Neutron energy versus channel number calibration.

Figure 28: Energy width calibration of the flight pulse height analyzer.

Figure 29: Compton electron energy versus laboratory pha channel number.
Neutron Leakage Current (cm$^2$ sec $^{-1}$)

Linnenfelter (1963)
Armstrong & Chandler (1972)
Wilson, Lambotte, Biroche (1969)
Freden & White (1962)

Neutron Leakage Current (cm$^2$ sec $^{-1}$)

Neutron Energy (MeV)

FIGURE 1
Atmospheric Gamma Ray Spectrum

\[ \lambda = 40^\circ \text{N} \]

3.5 g/cm²

Flux (photons/cm² sec Mev)

Photon Energy (Mev)

2. Puskin (1970)
5. This Experiment

Figure 2
Pulse Height Response - NE 213

- P.W. Benjamin
- T.G. Masterson (NE 218)
- Rothberg et al.
- Betnohor, et al.
- Burrus, et al.
- This Experiment $E_\pi = 220E_p^{1.41}$

**FIGURE 3**
Number of Events

A ——— Ideal Rectangular Distribution
B ——— Low Energy Neutrons—Effects of multiple scattering near upper energy edge.
C ——— High Energy Neutrons—Effects of non-linear response

FIGURE 4
FIGURE 5

- $H(n,n')H$ Horsley, NDT-A2, 243 (1967)
- $C(n,\alpha)$ ENDF/B Version II, March 1971, Oak Ridge Lab (1971)
- $H(n,n')H$ Kurz, Table 3, NDT-A6, 137 (1971)
- $C^2(n,n')$ P. Jørgensen et al., NDT-A1, 103 (1964)
- $(n-C)_\text{Total}$ Kurz (1964)
- $C(n,p)$ Kurz (1964)
- $C(n,p')$ Kurz (1964)
- $(n,Al)$ Total Gollnitz et al. (1969)

NDT = Nuclear Data Tables
Absorption Probability, $N(E)$

$N(E) = N_0(E) \frac{1 - \exp(-\rho x \sigma)}{N_0(E) = 10^E - 2.0}$
FIGURE 9

BALLOON FLIGHT TRAIN

6' CABLES

SCIENTIFIC INSTRUMENTS

30 lbs

50 lbs

CABLE

55 lbs

2.25'

23.75'

10'

1.5'

SCIENTIFIC INSTRUMENT

CRUSH PAD

BALLAST

NCAR INST.
Count Rates
Palestine, Texas
April 3, 1970

FIGURE 10
Count Rates
Ft. Churchill, Canada
July 5, 1970

![Graph showing count rates for electron and proton recoils over time.](image)

**Figure 11**
FIGURE 13
Proton Recoil Spectrum
Palestine, April 3, 1970
3.5 g/cm²
7.0 Hours

FIGURE 15
Proton Recoil Spectrum
Ft. Churchill July 5, 1970
6.0 g/cm²
11.0 Hours

Protons / MeV

Energy (Mev)

Figure 16
Pulse Height Distributions
Proton Recolls
Ft.Churchill July 5, 1970

FIGURE 17
Counts/Channel

Pulse Height Distributions
Proton Recoils
Palestine, Texas
April 3, 1970

FIGURE 18
Pulse Height Distribution
Proton Recoils
Palestine April 3, 1970

Counts/Channel

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<th>( A_i )</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>1.7</td>
<td>1.7</td>
<td>1.1</td>
<td>1.1</td>
<td>2.0</td>
<td>1.04</td>
<td>22.9</td>
</tr>
<tr>
<td>Calculated</td>
<td>1.5</td>
<td>0.9</td>
<td>0.3</td>
<td>0.0</td>
<td>2.0</td>
<td>0.50</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
<td>0.27</td>
<td>10.2</td>
</tr>
</tbody>
</table>

FIGURE 19
Electron Recoil Spectrum
Ft. Churchill July 5, 1970
6.0 g/cm²
11.0 Hours

Electrons / Mev

Energy (Mev)

FIGURE 20
Electron Recoil Spectrum
Palestine, April 3, 1970
3.5 g/cm²
7.8 Hours

FIGURE 21
Electron Recoil Spectrum
Palestine, Texas
April 3, 1970

Count Rate Flux (counts/cm² sec MeV)

- Observed
- Calculated From:
  - $0.625 \times 10^{-22}$ for $E < 4$ MeV
  - $0.357 \times 10^{-19}$ for $4 \leq E \leq 30$ MeV

Electron Recoil Energy (MeV)

Figure 22
Electron Recoil Spectrum
Ft. Churchill
July 5, 1970

Observed
Calculated From:
\[ \begin{align*}
1.05E^{-2.2} & \quad 1 \leq E \leq 4 \text{ Mev} \\
0.38E^{-1.5} & \quad 4 \leq E \leq 30 \text{ Mev}
\end{align*} \]
Neutron Leakage Current (cm² sec Mev⁻¹)

Neutron Leakage
Solar Minimum
40° Geomagnetic Latitude

Albernhe and Telon (1969)
Haynes (1964)
Jenkins, et al (1971)
White, et al (1972)
Lingenfelter (1963)
Baird and Wilson (1966)
This Experiment

FIGURE 24
Counts/Channel

Am-Be gammas
(Background subtracted)

Figure 25d
Proton Recoil Spectra

$H^3(p,n)He^3$ Neutrons

$\theta_{lab}=0^\circ$

FIGURE 26
FIGURE 27

- D-T Calibration: 9/25/71
- D-T Corrected to 2/4/72 gain
- Lowell Calibration: 2/4/72
Maximum Compton Electron Energy (MeV)

![Graph showing maximum Compton electron energy for various isotopes.]