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# THE OSO 1
# SOLAR NEUTRON EXPERIMENT



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## ABSTRACT

$BF_3$ counters on OSO 1 were used to look for solar neutrons by trying to observe a diurnal variation in count rate. No effect was observed and an upper limit was placed on the solar neutron flux at the earth of $J_n < 2 \times 10^{-3}$ neut/cm$^2$-sec of 10 Kev < $E_n$ < 10 Mev for the period March to May 1962. No proton producing flares occurred during this time so the most obvious source of solar neutrons could not be studied. The emulsion experiment of Apparao, et al, flown during this period which seemed to indicate solar neutrons has probably been misinterpreted.

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## INTRODUCTION

There have been conjectures for some time that neutrons may arrive at the earth from the sun (Biermann et al, 1951). Hess (1962) considered briefly several processes whereby solar neutrons might arrive at the earth. However, thermonuclear reactions in the solar atmosphere seem to yield a negligibly small neutron flux apparently even in connection with large flares. Leakage of neutrons from the interior of the sun where some are made in thermonuclear reactions is vanishingly small. The only apparent source of reasonable fluxes of solar neutrons at the earth is from solar proton events.

In some early experiments where there was an opportunity to detect solar neutrons (Swetnik et al, 1952; Haymes, 1959) there were some effects seen which seem to indicate a possible solar effect. Swetnik et al, found that the count rate of a balloon-borne detector for a few hours before sunset was about 17% larger than the count rate after sunset. Haymes found a thermal neutron peak in count rate of a balloon-borne detector about a half hour before sunset on two flights during 1958, but not on flights in 1963. This peak might be interpreted as the result of a nuclear transition effect in the earth's atmosphere. When the neutrons have entered the atmosphere a distance of one interaction mean free path ($\lambda \sim 60$ gm/cm$^2$) there should be a peak in the secondary particle flux as is observed in experiments at accelerators. Therefore a balloon-borne neutron detector very near the top of the atmosphere might find a peak in count rate somewhat before sunset when the neutrons grazing the atmosphere pass through $\sim 60$ gms/cm$^2$ of air to reach the balloon.

However, there is the possibility that the effects observed by Swetnik and Haymes are instrumental associated with changes in balloon altitude at sunset or changes in detector temperature. Haymes (1965) has given a good review of this matter.

It has also been suggested that the decay of solar neutrons (Simpson 1963) may be the source of the flux of protons below 200 Mev observed at the earth by Vogt (1962), Meyer and Vogt (1963) and Stone (1964). However, it is now thought that these low energy protons may be secondaries produced in the earth's atmosphere (Frier and Waddington, 1965). Bame and Asbridge (1966), using moderated $He^3$ proportional counters on the Vela satellites, have searched for a steady state flux of solar neutrons by studying the detector count rates during eclipse of the moon or earth. Assuming the neutrons had an energy spectrum similar to terrestrial albedo neutrons they could have detected a flux of .01 neutrons/cm$^2$-sec but observed nothing.

Bame and Asbridge (1966) also looked for neutron bursts following two solar flares of importance 3 and also several flares showing Type IV radio noise. No bursts were observed although $1.5 \times 10^3$ neut/cm$^2$ would have been seen.

Haymes (1964) in a series of balloon flights in 1963 had balloons at an altitude of ~125,000 ft. for periods up to 24 hours. By measuring the day-to-night flux ratio in the energy range 1-14 Mev, he could put an upper limit on the solar neutron flux at the earth of 0.02 neutrons/$cm^2$-sec assuming that the solar spectrum at the earth is similar to that of the albedo neutrons.

Apparao et al (1966) feel that they may have found solar neutrons by studying the angular distribution of knock-on protons found in emulsions flown on balloons. I do not feel that they have documented their case very strongly and I am of the opinion they did not observe solar neutrons. I will return to this later.

In summary, there have been several opportunities to observe solar neutrons experimentally but so far no definite positive results have been achieved.

Hess (1962) suggested that there should be a measurable flux of solar neutrons at the earth following a major solar flare in which solar protons were produced. The model proposed for the production of the neutrons had half of the energetic protons produced in the solar flare going downward into the dense solar atmosphere interacting with helium and heavier elements in the sun to produce spallation and evaporation neutrons. An estimate made at that time was that for a solar proton event producing $10^9$ protons/$cm^2$ at the earth there should be an average neutron flux at the earth of $\sim$20 neutrons/$cm^2$/sec for a time of $\sim$1000 seconds. Lingenfelter et al (1965) have made a much more detailed and quantitative study of solar neutrons from flares based on this same model. They find that the time average solar neutron flux above 10 Mev at 1 AU over the last solar cycle considering all the solar proton events is $3 \times 10^{-3}$/neutrons/$cm^2$-sec.

Lingenfelter et al (1965) also considered neutron production during the November 12, 1960, solar proton event for which the time integrated solar proton flux was $1.4 \times 10^9$ protons/cm$^2$ above 30 Mev. They find the total solar neutron flux above 10 Mev reaching the earth after the flare should be about $2 \times 10^4$ neutrons/cm$^2$ with a peak intensity of about 25 neutrons/cm$^2$-sec with an energy of about 200 Mev about 15 minutes after the production at the flare. (These numbers have been revised down by a factor of 3 by Lingenfelter et al from their earlier estimates.) The energy spectrum at the earth calculated by Lingenfelter et al for the November 12, 1960 event is shown in Figure 1. Certain other models of flares (Sturrock 1966) would have most of the particles accelerated upwards which would probably result in smaller neutron production. This means that the detection of flare-related solar neutrons might distinguish between certain flare models.

## The OSO 1 Experiment

The primary purpose of the neutron detector flown on the OSO 1 in March 1962 was to try to detect solar protons. The detector was a pair of moderated $BF_3$ proportional counters with one enriched in $B^{10}$ and one depleted in $B^{10}$. The moderator was epoxy about 1-1/2 inches thick. The efficiency of the counter for detecting neutrons was roughly 2 count per neutron per cm$^2$ and was essentially independent of energy in the rage 10 kev to 10 Mev. This detector was rather similar to one flown earlier by Hess and Starnes (1960).

The data from this detector is not especially useful in producing information about the terrestrial neutron flux because of the significant contribution to its counting rate from locally produced neutrons. Terrestrial neutron fluxes are fairly well known now for energies below 10 Mev. A good summary of recent material on this subject is given in the Summary of the Conference on the Earth's Albedo Neutron Flux held at the Applied Physics Lab of Johns Hopkins University on October 15, 1963 (Williams and Bostrom 1963).

The detector was used on OSO 1 to try to detect solar neutrons by two techniques:

a. Diurnal variation of the count rate.

b. Pre-sunset increases as seen by Haymes (1959) which may be indicative of high energy neutrons.

The data for 538 orbits during the first three months of OSO have been combined to look for a diurnal variation in the count rate. The detector count rate varies with latitude because the terrestrial neutron source varies with latitude so the data has been sorted into day and night groups and into L intervals (where L is the McIlwain shell perimeter). The results of this analysis are shown in Table 1. It is seen that there is no evidence for a diurnal variation in the neutron count rate. If there was a 1% day-to-night variation it should have been seen. The charged particle detector flown by Schrader (my thanks to Dr. Schrader and Dr. Waggoner for allowing me to use this data before publication) on OSO 1 was also studied to look for diurnal variations of protons or electrons. The day/night count rate ratio was always statistically N/D = 1 showing that the charged particles here also show no diurnal variations. Figure 2 shows data from the $B^{10}$ $F_3$ detector for a typical pass of the OSO 1 satellite. The strong peak shown is due to the detector passing thru the lower edge of the proton radiation belt in the South Atlantic anomaly. All data in a region -90° to +60° longitude and +10° to -90° latitude was excluded from the analysis and also orbits showing telemetry noise or other suspicious data was extended. The data was further subdivided from that shown in Table 1 into 10 intervals in time covering the three-month period. Each of these intervals had roughly 50 orbits of data. This was done to see if in any relatively short time a diurnal variation might be noticed. No positive effect was seen. Data was also scanned for those orbits when there were flares of importance 2 or greater observed, as shown below.

| DATE | FLARE IMPORTANCE |
|---|---|
| March 13 | 2+ |
| March 17 | 2 |
| March 20 | 2 |
| March 21 | 2 |
| March 22 | 3 |

No neutron effects were found associated with these orbits. There were no PCA events during this three-month period of OSO-1's lifetime, so we did not have an opportunity to look for neutrons from the most obvious source – namely solar flares. The previously reported (Williams and Bostrom 1963) variations in count rate for this present experiment are now known to be spurious and related to telemetry noise. No significant time variations of the neutron flux were observed.

Using the value from Lingenfelter (1963) that the neutron flux above the earth's atmosphere above the equator is 0.11 neutron/cm$^2$-sec, estimating the local production of neutrons was equal to this and using the fact from Table 1 that the diurnal variation was less than 1% we can say that during the period March to May of 1962 the solar neutron flux detectable at the earth was $J_{-} < 2 \times 10^{-3}$ neutrons/cm$^2$-sec in the energy range 10 kev $< E_n <$ 10 Mev. The fact that the expected solar neutrons fall in the energy range 10-300 Mev essentially above the energy range of the present detector does not mean that we would not detect them. The detector used should have a quite high efficiency for these high energy neutrons as a result of atmospheric albedo of the neutrons. It was shown by Killeen, Hess and Lingenfelter (1964) that the albedo from the earth's atmosphere for neutrons of 1 ev $\sim E_n \sim$ 10 Mev is remarkably high and remarkably independent of the zenith angle. A typical average neutron albedo is 0.7. This atmospheric albedo should remain high up to 100 Mev or more. The albedo neutrons are partially thermalized and should be easily detectable by the modified $BF_3$ counter so the solar neutron flux should be detectable either directly or by its albedo if the neutrons are of too high energy to be measured efficiently by the detector directly.

The second technique used to look for solar neutrons in the OSO 1 experiment was the pre-sunset count rate increase seen earlier by Haymes (1959). Figure 3 shows a summary of 61 orbits of data combined in terms of the angle of the sun above the horizon to look for this effect. There is no obvious effect. A 20% peak would have been seen. I am not at all sure that even if an effect is seen it can be understood in terms of a nuclear transition curve as was first considered. The fact that the neutron albedo flux from neutrons incident on the atmosphere is essentially independent of the zenith angle means that there really should not be a pre-sunset increase at all. If the albedo were truly independent of the zenith angle all the way to 90° then one would just expect a daytime enhancement without a pre-sunset peak.

In any case, such a peak does not appear in the present data.

## Comparison with Other Experiments

This present experiment sets a lower limit to the quiet time solar neutron flux of 10 kev < $E_n$ < 10 Mev than given by previous measurements of Bame et al (1966) or Haymes (1964). This experiment says nothing about flare produced neutrons since no large flares or solar proton events occurred during the experiment.

The experiment disagrees with results of Apparao et al (1966) who claimed to have seen a solar neutron flux of $J_n$ = .045 neut/cm$^2$-sec of 20 < E < 160 Mev essentially during quiet times. (An earlier value of $J_n$ = .015 was corrected upwards by Apparao et al by a factor of $\pi$.) The technique used by Apparao et al is subject to considerable uncertainty. They studied the one prong stars in nuclear emulsions flown on balloons at ~10 gm/cm$^2$ depth in India in March 1962. They tried to consider only these events that had involved hydrogen nuclei in the emulsion (which is difficult to do) and by kinematics to get a rough angular distribution of neutrons of 20 < $E_n$ < 160 Mev. They assumed the neutron was traveling in the direction of the observed knock-on proton which can be wrong by as much as 90° but which may not be too serious. This resulted in a measured down/up ratio of

$$\frac{J \text{ down}}{J \text{ up}} = \frac{5.1 \pm 0.9}{6.5 \pm 1.0}$$

By using a qualitative argument about what this ratio should be, Apparao et al conclude that this ratio is too nearly unity to be solely terrestrial and deduce a solar flux from it. There has been no quantitative calculation of the down/up ratio, so it may really not be very different from unity. The angular distribution for terrestrial neutrons is expected to be somewhat anisotropic. For high energy neutrons it is expected (Hess et al, 1961) that the ratio

$$\frac{J \text{ horizontal}}{J \text{ up}}$$

will be larger than one. Without a quantitative calculation of the down/up ratio, the only convincing way to show that the measured value is not consistent with terrestrial neutrons alone would be to show a diurnal variation in the ratio. If a nighttime flight showed a significantly smaller down/up ratio, that would be interesting.

A solar flare occurred 6 hours before the start of the Apparao et al emulsion experiment but that could hardly have affected the results. Two hours after neutron production has occurred on the sun, those arriving at the earth will have $E_n$ = 4 Mev (See Figure 1), considerably below the range of interest of Apparao et al. The proton production associated with a flare is commonly thought to occur in a matter of minutes at the time of the flare (Webber 1964). The measurement of Apparao et al (1966) must be considered a quiet time solar neutron flux not related to the flare.

The OSO 1 neutron experiment was going on at the same time as the Apparao et al emulsion experiment was flown on March 23, 1962. This present report shows that the OSO experiment did not detect a steady state quiet time solar neutron flux although it would have seen one a factor of 20 smaller than that claimed by Apparao et al. The only reason why the OSO experiment might have missed such a quiet time neutron flux might be because the energy range covered by the detector is different than that covered by Apparao. However, as stated before, the present experiment has a reasonably good efficiency for counting neutrons of $E_n \sim 100$ Mev by atmospheric albedo. It seems very unlikely that a flux of $J_n = .045$ neut/cm$^2$-sec of $20 < E_n < 160$ Mev neutrons would not have been detected by the present experiment.

A second paper by the Tata group (Daniel et al 1966) presents other evidence for the emission of high energy neutrons from the sun. They used a scintillator-spark chamber assembly capable of measuring neutrons of $E_n < 50$ Mev flown on a balloon to about 11 gm/cm$^2$ on April 15, 1966, from India. Above the Pfotzer maximum, they observed a count rate decrease and then increase of about a factor of 2 over a period of about 90 minutes. They claim that this count rate increase is due to an average solar neutron flux of $\sim .10$ neut/cm$^2$-sec of $50 < E_n < 500$ Mev over 1-1/2 hours which may be related to a modest brightening of a sun spot group which they class as a sub-flare. This seems very unconvincing to us and to call this "positive evidence for the emission of high energy neutrons from the sun" as Daniel et al. do is in our opinion a gross overstatement. I feel it is much more likely that it is due to instrumental trouble.

If a subflare can generate neutron fluxes of 0.1 neut/cm$^2$-sec at the earth, it seems hard to believe that this has never been seen in cosmic ray experiments.

There is good reason for continuing the search for solar neutrons especially in relation to solar flares. We would suggest that all future attempts to look for solar neutrons should be of one of two types. Either

a. A highly directional neutron detector should be used outside the earth's atmosphere to uniquely identify the sun as the neutron source, or

b. A time variation should be studied such as a diurnal variation or a good sized transient related to a class 2 or 3 solar flare in such a way that charged particles don't contribute.

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Table 1
Count Rates of the $B^{10}$ $F_3$ Counter for Different L Intervals ($\Delta L = .1$) for Day and Night

| L | $CR_{Day}$ | $CR_{Night}$ | $\frac{CR_D}{CR_N}$ |
|---|---|---|---|
| 1.05 | .567 | .579 | .979 ± .009 |
| 1.15 | .680 | .700 | .971 ± .008 |
| 1.25 | .821 | .828 | .991 ± .008 |
| 1.35 | 1.000 | 1.000 | 1.000 ± .009 |
| 1.45 | 1.250 | 1.213 | 1.030 ± .011 |
| 1.55 | 1.470 | 1.430 | 1.028 ± .012 |
| 1.65 | 1.679 | 1.651 | 1.017 ± .012 |
| 1.75 | 1.932 | 1.910 | 1.011 ± .012 |
| 1.85 | 2.153 | 2.075 | 1.038 ± .013 |
| 1.95 | 2.343 | 2.248 | 1.042 ± .013 |
| 2.05 | 2.420 | 2.355 | 1.028 ± .014 |
| 2.15 | 2.635 | 2.580 | 1.021 ± .017 |
| 1.0 to 1.7 | .855 ± .0026 | .852 ± .0034 | 1.003 ± .005 |

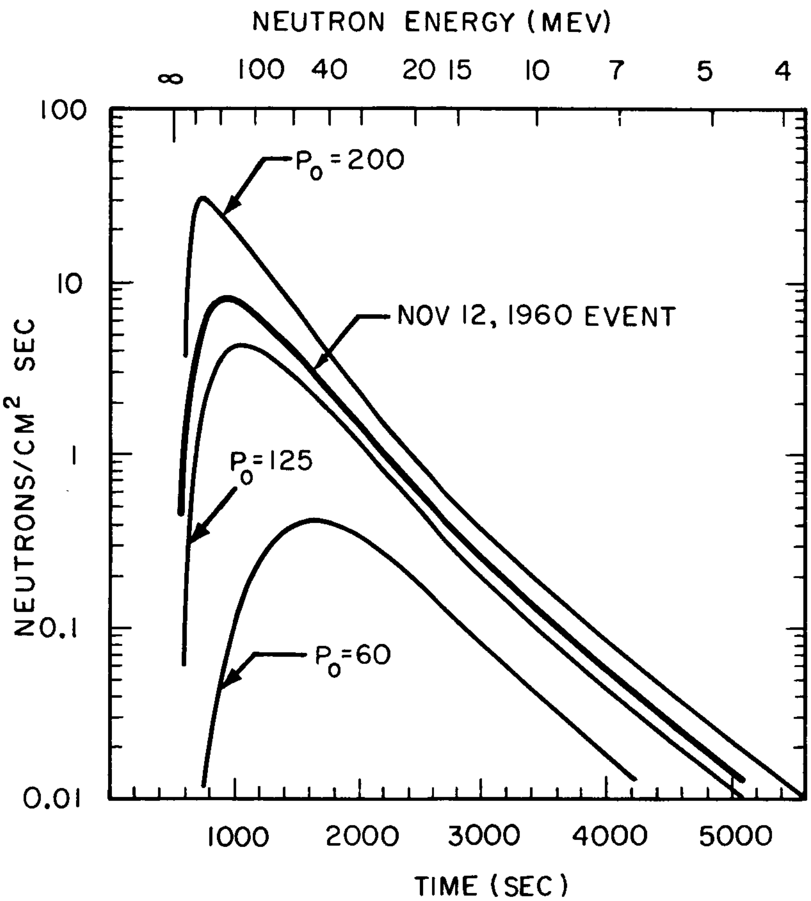


Figure 1–The integral solar neutron flux at 1 AU as a function of time after the release of accelerated protons from the flare region. The upper scale gives the mean neutron energy arriving at times shown on the lower scale. (Lingenfelter et al 1965)

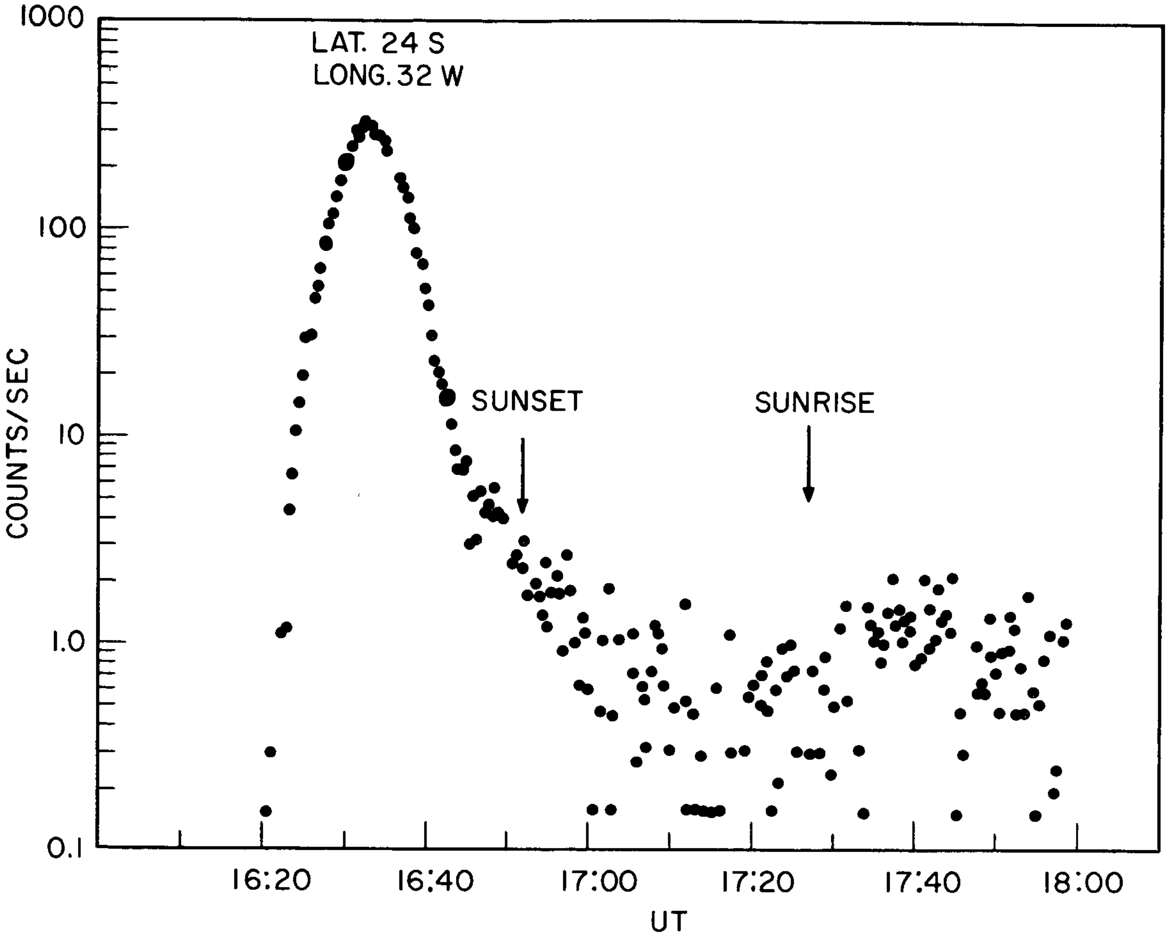


Figure 2–OSO $B^{10}F_3$ detector count rate on orbit 76 March 12, 1962

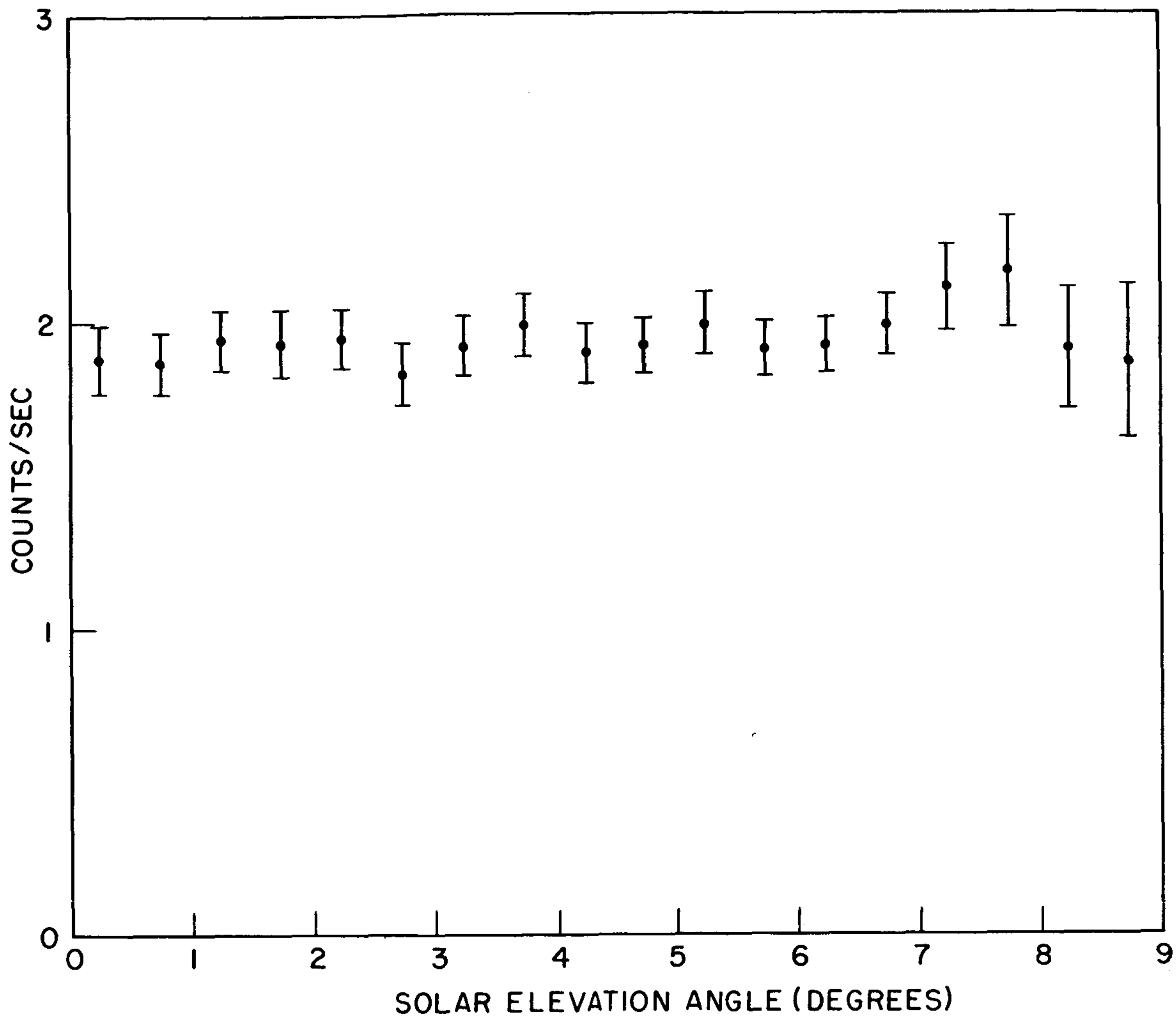


Figure 3–OSO $B^{10}F_3$ detector count rate vs angle of elevation of the sun above the horizon summed over 61 orbits. No pre–sunset increase is seen here