An Upper Limit on the Quiet Time Solar Neutron Flux at Energies > 60 MeV

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Abstract

During the course of a series of balloon flights with Cerenkov-scintillation counters designed to measure the energy spectrum of charged primary cosmic ray nuclei it has been possible to set limits on the quiet time solar emission of neutrons in the approximate energy range above 60 MeV. These limits (which are nearly an order of magnitude smaller than previously reported), were obtained by comparing the intensity of secondary protons at $\simeq$ 12 g/cm^2 atmospheric depth near the equator as measured on two balloon flights - one with the detector telescope oriented vertically and the other with the detector telescope oriented at a zenith angle of $\simeq 50°$ and rotating in azimuth. This latter telescope alternately pointed at the sun and at an angle 90° to the sun. The absence of any excess secondary proton flux when the detector was pointing at the sun allows us to set a 2 σ limit of $<$ 1.0 protons/m^2-ster-sec in the energy range 60-320 MeV as being produced in the atmosphere above the detector by solar neutrons. Considering the efficiency of proton production by neutrons in $\simeq$ 12 g/cm^2 of air we are able to set an upper limit of 24 solar neutrons/m^2-sec $>$ 100 MeV, assuming a differential neutron spectrum at the earth $\simeq E^{-2}$. Further details on the limits of solar neutrons in various differential energy intervals are presented and these results are compared with other observations.

Introduction

Despite a considerable history of studies directed toward the observation of neutrons from the sun, until recently no positive evidence for these particles existed. On the basis of measurements of star production in an emulsion flown on March 23, 1962, Apparao et.al., (1966), claim a flux of 465 $\pm$ 190 neutrons/m^2-sec from the sun in the energy interval 20-160 MeV. This measurement occurred some 6-12 hours after an optical flare of magnitude 3, however since no particle intensity variations or geophysical effects were recorded at the earth, it is probably more appropriate to consider this observation as applying to quiet sun conditions. In any case such a large flux of high energy neutrons has rather significant implications regarding the magnitude of high energy nuclear processes on the sun. Although the above neutron intensity is $\simeq$ 10% of the primary cosmic ray flux at high latitudes it actually exceeds the flux of primary cosmic ray nucleons near the equator! It is nevertheless lower than any previous limit placed on high energy neutrons from the sun; either at quiet times or during flare conditions, and is comparable with the upper limit of 100 neutrons/m^2-sec, (for neutrons of energy between 1 and 20 MeV), set in a recent satellite experiment by Bame and Asbridge, (1966). These relatively high limits attest to the difficulties involved in detecting and measuring the energy of neutrons in the presence of the primary cosmic ray background. It may also be noted here that if neutrons are produced at the sun with energies extending up to a few hundred MeV, the high energy ones will have the highest probability of reaching the earth without decay. The competition between the production spectrum of neutrons at the sun, assumed to be rising towards lower energies, and the decay of the neutrons in travelling to the earth will produce a differential neutron spectrum with a maximum in the energy range 40-80 MeV at the earth-this maximum moving to higher energies for flatter production spectra. Because the spectrum observed at the earth is dominated by the decay of the neutrons at low energies it will fall off exponentially thus greatly diminishing the likelihood of observing any solar neutrons at all below about 20 MeV.

In the experiment to be discussed here, limits approximately an order of magnitude lower than any previously reported are set on the incidence of solar neutrons in the energy range above 60 MeV by means of directional measurements of atmospheric protons in the energy range 60-320 MeV in a series of balloon flights made near the geomagnetic equator.

The Experiment

The detector used in these studies consists of a two element Cerenkov-scintillation counter telescope, with a geometrical factor ≈ 50 st cm^2. The details of this telescope and its response to particles of various energies have been discussed in a number of publications (Ormes and Webber, 1965), and will not be repeated here. Suffice to say that this instrument is capable of measuring the spectrum of protons in the energy range from 50 MeV to ≈ 1 BeV, and with a sufficient counting rate to determine the spectrum of secondary protons produced in the atmosphere as a function of altitude even on an equatorial balloon flight.

The observations reported here were made on two balloon flights launched from Tucuman, Argentina on August 1 and August 8, 1964. The solar activity was relatively quiet for the periods of these two flights. The geomagnetic cut-off rigidity at this location, (27° S geographic latitude and 65° W geographic longitude) is 12.1 BV. The main purpose of these flights was to measure the integral intensity of primary protons and heavier nuclei above the cut-off rigidities appropriate to this location. During the first flight, on August 1, the equipment, pointing at the zenith, floated at an altitude of 9.2 g/cm^2 between 1000-1400 hours local time after first ascending to an altitude corresponding to 6.5 g/cm^2 residual atmosphere. For the second flight the telescope was pointed at a constant zenith angle of 50° and rotated in azimuth with a rotation period of 15 minutes. In this way the east-west difference in cut-off rigidities near the equator was used to obtain the spectrum of primary protons and heavier nuclei in the range 9.8 - 18.0 BV rigidity. This flight floated at a vertical depth of 8.6 g/cm^2 between 1030-1330 hours local time after first ascending to 5.8 g/cm^2, slightly higher than for the first flight.

The conditions relating to these two flights were particularly advantageous for the study of possible effects of solar neutrons. At this time of the year at local noon the solar zenith angle is approximately 45° to the north. The opening half angle of the telescope is ≈ 25°. Thus during the first flight the effective angle of the telescope with the respect to the sun for the time period ± 2 hours to the local noon is very closely 45°. For the second flight, however, the telescope alternately points almost directly at the sun (to the north) and 90° to the earth-sun line (to the south) as it rotates in azimuth.

In this experiment the residual atmosphere above the instrument is used as the "detector" of the solar neutrons through the nuclear interactions and knock-on protons they produce. This atmospheric "detector" is not as efficient as one containing primarily hydrogen, but the secondary effects of the neutrons are actually easier to interpret at these higher energies. The relative effects of solar neutrons in the north pointing and south pointing telescopes can be estimated by considering those simple collisions with air nuclei in which an elastically scattered secondary proton emerges. The energies of the incident neutron and scattered proton and the angle of emergence of the scattered proton relative to the direction of the incident neutron are given by

$$E_p = E_n \cos^2 \theta$$

In addition to the increasing energy degradation with increasing scattering angle the differential scattering cross section also decreases rapidly with increasing scattering angle. As a result, for secondary protons arising from np scattering, the north pointing telescope will "see" solar neutrons with a relatively high efficiency whereas the south pointing telescope, which at no time between 1000 and 1400 hours local time accepts protons scattered with an angle $< 60°$ with respect to incident solar neutrons, is effectively "blind" to any of these neutrons. Multiple scattering and secondary protons emitted from interactions of neutrons with air nuclei will tend to make these limits fuzzy but for this later source (which actually dominates at the energies discussed here), the protons will still preserve to a high degree the direction of the incident neutrons. This is particularly true for the emission of protons with energy > 60 MeV from "stars" produced by neutrons incident on air nuclei.

Results, Interpretation and Discussion

The differential spectra of protons measured during the previously mentioned time intervals for the two flights are shown in Figure 1. Several aspects of the data presented in this figure are worthy of note. First considering the vertical flight, we note that the intensity of (secondary) protons has been measured as a function of atmospheric depth on balloon flights with this detector pointed vertically at 5 other geographic latitudes ranging from 28° N to 48° N, when the solar zenith angle ranges from $\approx 20°$ to $\approx 65°$. These measurements have given a fairly complete picture on how the secondary proton component varies with atmospheric depth and particularly with geomagnetic cut-off rigidity (and will, in fact, be used later to determine the efficiency of production of secondary protons in the atmosphere by incident solar neutrons).

Table I

Secondary Proton Intensities in the
Energy Range 60-320 MeV

Flight-Direction	Total Number of Secondary Protons Observed	Intensity of Secondary Protons (particles/m^2-ster-sec)
August 1 - vertical	1716	26.9 ± 0.8
August 8 - east	804	33.0 ± 1.1
west	636	40.7 ± 1.5
north	534	34.5 ± 1.6
south	495	37.0 ± 1.8

This picture is consistent with all of the secondary protons being accounted for through nuclear interactions of the primary radiation in the residual atmosphere or through reentrant albedo protons without the necessity of envoking a further zenith angle dependent solar source. The limits that one could put on the solar source through these arguements are naturally most restrictive for measurements near the equator where the primary source is smallest. They suggest that not more than about 30% of the protons observed at 9.2 g/cm^2 in the vertical equatorial flight could be due to the solar neutron source. However since the limits set by the rotating flight are nearly a factor of 5 lower than this we will not pursue this approach further.

In comparing the results of the vertical and rotating flights we notice that the average proton intensity in the north-south direction is some 30-40% higher than for the vertical direction. This is accounted for by the expected growth of secondary protons with increasing atmospheric depth and the fact that the slant depth of the rotating flight was 12.9 g/cm^2 as opposed to 9.2 g/cm^2 for the vertical flight. The ratio of $\approx$ 1.25 for the west pointing secondary proton intensity to the east pointing secondary proton intensity is directly related to the differences in geomagnetic cut-offs in the two directions.

The most important aspects of the data relevant to the possible presence of solar neutrons are the north-south intensities of secondary protons which are seen to be approximately equal and to generally lie in between the east-west intensities, as would be expected on the basis of the geomagnetic cut-offs in each direction. Table I summarizes the total intensities of secondary protons in the energy interval 60-320 MeV for the different flights. The total difference in north-south intensities in the 60-320 MeV interval is -2.5 ± 2.4 particles/m^2-ster-sec. The north intensity is also consistent with the intensity of 36.5 particles/m^2-ster-sec at this slant depth expected on the basis of the vertical flight and a linear growth with atmospheric depth of the secondary protons; and an intensity of 38 particles/m^2-ster-sec determined on the basis of the relative cut-off rigidities in the east, north and west directions.

On the basis of the measured intensity of 34.5 ± 1.6 secondary protons/m^2-ster-sec in the north direction we would have to conclude that to a confidence limit of 2 σ not more than 1.0 protons/m^2-ster-sec in the energy range 60-320 MeV the north pointing telescope ($\approx$3 % of those actually measured at this depth), coul be produced by solar neutrons. Similar arguements can be used to set limits on the protons appearing in each of the north pointing differential energy intervals that could arise from solar neutrons. The remaining task is considerably more difficult, namely to translate

Table II

Energy Dependence of Secondary Proton Production

in 12.9 g/cm^2 of Atmosphere by Primary Nucleons

Location	Cut-Off Energy (BeV) (Protons)	Primary Proton Intensity	Secondary Proton Intensity at 12.9 g/cm^2 (60-320 MeV)	Efficiency (%)
		(particles/m^2-ster-sec)		
Tucuman, Arg.	11.2	170	37.5	22.1
Kerrville, Tex.	4.6	525	112	21.2
Fayetteville, Ark.	2.0	1020	207	19.9
Minneapolis, Minn.	0.6	1860	323	17.4
Devils Lake, N.D.	0.4	2220	368	16.5
Ely, Minn.	0.32	2630	405	15.4

these limiting proton intensities into limits on the fluxes of solar neutrons incident on the top of the atmosphere. As noted earlier air is not the ideal "detector" of neutrons. However at the energies considered here, neutrons provide a fairly efficient source of secondary protons through nuclear interactions with air nuclei in the 1st few g/cm^2 of the atmosphere.

We shall strive for a limit on the solar neutron flux accurate to within a factor of two and begin by noting that essentially two mechanisms exist whereby such neutrons might produce protons in the atmosphere above the detector, (1) neutron elastic collisions with air nucleons-leading to the emission of a single "scattered" proton and, (2) nuclear interactions of the neutrons with air nuclei resulting in one or more secondary protons including one in the energy range of our measurement. Information on the relevant cross sections for mechanism (1) in air is very incomplete in the energy range of our interest, as a result it is impossible to make a rigorous estimate of the magnitude this process. For collisions of neutrons with air nuclei, mechanism (1) is actually a sub-class of the more general process (2). (Arising when only one nucleon, a proton, is emitted and the excitation of the residual nucleus is negligible). Process (2) is amenable to a fairly rigorous calculation by taking into account the number and angular distribution of secondary protons as a function of energy resulting from nuclear interactions of energetic nucleons with air nuclei. We propose another approach, however, utilizing our own measurements of secondary protons in the energy range 60-320 MeV as a function of geomagnetic latitude. This analysis results in an "efficiency" as a function of incident primary (nucleon) energy for the production of secondary protons observed at a given atmospheric depth. It is completely equivalent to the yield function or coupling coefficient approach that is used to relate counting rates of neutron monitors in the atmosphere and near sea level to the intensity of the primary cosmic radiation at the top of the atmosphere (Dorman, 1957).

In Table II we show the results of six vertical flights at locations with cut-off energies for protons from 320 MeV to 11.2 BeV. The measured intensity of primary protons above the cut-off energy is shown (Ormes and Webber, 1965) along with the secondary proton intensity between 60-320 MeV measured at an atmospheric depth of 12.9 g/cm^2. The "efficiency" per incident nucleon for producing secondary protons in this energy range at this depth is shown in the final column. In Figure 2 this data is converted into a differential "efficiency" covering the primary nucleon range above 320 MeV. It is seen that this "efficiency" is a slowly varying function of primary energy increasing from ≈ 0.1 at 320 MeV to 0.2 at energies > 10 BeV.

Although nuclear interactions of primary protons are the dominant producer of secondary protons in the 60-320 MeV energy range at 12.9 g/cm^2 they are not the sole one. Nuclear interactions of helium and heavier nuclei are also important and re-entrant albedo protons make a contribution - although at these depths this later contribution is only ≈ 10-20% of the direct primary proton source, (Webber, 1966). Almost 1/2 of all primary cosmic ray nucleons above a given cut-off rigidity are in the form of helium and heavier nuclei (Webber, 1966). The energy of each of these nucleons is ~ 1/2 of the primary protons, however, because the $\frac{A}{Z}$ ratio of these nuclei is 2. As a result these nucleons will be somewhat less efficient than protons in producing secondary protons.

At these energies it is generally assumed (although difficult to verify) that the nucleons contained in the heavier nuclei act independently and that secondary proton production by protons and neutrons of the same energy are equivalent. If the first part of this assumption is incorrect then the heavier nuclei will not be as efficient per nucleon in creating secondary protons, in which case the contribution by helium and heavier nuclei will be over-estimated. With regard to the second assumption, Metropolis et.al. (1958), have presented extensive calculations of intra-nuclear cascade processes which lead to the result that p going to p (within our energy range) is almost twice as efficient as n going to p for Al target nuclei (eg. incident protons are more efficient at producing energetic secondary protons whereas incident neutrons are more likely to produce energetic secondary neutrons). This favoritism is enhanced in nuclei heavier than Al; partly because of the increased n/p ratio in the nucleus. Hence, although the calculations of Metropolis et.al. do not cover air nuclei we may suppose that incident protons are somewhat less than a factor of two more efficient in air than incident neutrons in producing secondary protons in the energy range of observation.

In view of the weak dependence of the "efficiency" of production of secondary protons on primary energy we shall take a mean "efficiency" of 0.15 as applying to all primary nucleon energies > 320 MeV. This must be reduced to approximately 0.07 allowing for the contributions of helium and heavier nuclei and re-entrant albedo protons and the somewhat lower "efficiency" of neutrons. (It should be noted that, taking an interaction mean free nucleons interact in the 12.9 g/cm^2 of atmosphere above the telescope. The measured "efficiency" of 0.1 implies that [illegible] 50% of these interactions produce at least one secondary proton in the energy range 60-320 MeV).

Assuming now that <u>all</u> of the "upper limit" of 1.0 excess protons/m^2-ster-sec at 12.9 g/cm^2 reported earlier are produced by solar neutrons above 320 MeV gives an upper limit of 15 neutrons/m^2-sec.* This is an obvious simplification to the real situation, since we should expect a continuous spectrum of solar neutrons at the earth extending at least down to energies at which decay becomes important. For further computational purposed let us assume a differential spectrum of solar neutrons at the earth of the form $\frac{dN}{dE} \sim E^{-2}$. In order to place limits on the contribution of neutrons with less than 320 MeV energy in such a spectrum to secondary protons in the 60-320 MeV range we must extend the efficiency curve presented in Figure 2 to lower energies. It is clear that the efficiency should decrease more rapidly with energy for neutrons < 320 MeV - reaching zero at an energy of 60 MeV. This decrease in efficiency should be at least as rapid as energy simply on the basis of the decreasing energy interval in which the secondary protons must be produced to be "counted". The dashed line in Figure 2 represents a decrease in efficiency $\approx E^{1.5}$ below 320 MeV, that is the E dependence noted above times the slower change in efficiency with energy observed [illegible] 320 MeV.

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*The conversion from the measured limits on the directional intensity of protons to the limiting unidirectional intensity of neutrons at the top of the atmosphere is further complicated by the "geometry" of the neutron detection. The conversion factor between protons/m^2-ster-sec and neutrons/m^2-sec in the particular measurement we have made must lie between the extreme limits of 0.3 and π. The value of π would arise if our detector were omni-directional and had an equal efficiency for detection in all directions. This is clearly not the case. The factor of 0.3 would result if all parts of the total area of $\approx$ 150 cm^2 of the first detector element in the telescope were equally efficient in detecting neutrons passing through it. Such a circumstance would arise only if the neutrons were detected within the equipment. It is also clearly not the case here and is mentioned only to illustrate the minimum limit for the conversion factor. In our case, where neutron detection is actually accomplished in the atmosphere above the detector we need to estimate an angular "detection" sensitivity in order to convert the directional (steradian) proton intensity measurement to the unidirectional neutron flux. Based on our earlier arguments we take a sensitivity $\sim \cos^2 \theta$ where θ is the angle with respect to the incident neutron. Integration over the upper hemisphere for a unidirectional source gives an effective solid angle of $\frac{\pi}{2}$ instead of π for an angle independent source. For simplicity and in view of the added fuzziness in directionality introduced by the continuously rotating telescope we have taken a conversion factor of 1.

With this efficiency and taking a differential spectrum $\approx E^{-2}$ above 100 MeV, we obtain

$$\frac{dN}{dE} \leq \frac{2400}{E^2} \quad (\text{neutrons/m}^2\text{-sec-MeV})$$

This limiting spectrum is shown in Figure 3. The integral flux above 100 MeV implied by this spectrum is $\leq$ 24 neutrons/m^2-sec. Modification of this spectrum for decreasing efficiency below 320 MeV is shown as the dotted line in the figure.

This spectrum is roughly similar to a nuclear spallation spectrum and is certainly reasonable based on a knowledge of typical solar proton spectrums observed at the earth. The limiting differential spectrums for assumed neutron spectrums $\approx E^{-1}$ and E^{-3} are shown by the shaded area in Figure 3.

Limits on the solar neutron intensity that can be set in two lower energy ranges, 60-100 MeV and 100-160 MeV, are also of interest. Utilizing the efficiencies presented in Figure 2 and assuming separately that the observed protons are produced only by solar neutrons in each of these two energy ranges we arrive at upper limits of 125 neutrons/m^2-sec and 75 neutrons/m^2-sec respectively in each of these energy ranges. These limits are also shown in Figure 3.

The data we have presented in this paper are compared in Figure 3 with the most definitive experimental results on (quiet time) solar neutrons at the earth obtained to date. Also shown are the limits between 20 and 80 MeV set by Roelof (1966), on the basis of attributing low energy protons measured in interplanetary space to the decay of solar neutrons enroute to the earth. These limits are at least 3 or 4 orders of magnitude lower than any direct experimental measurement below 80 MeV and must be regarded as realistic within our present understanding of the propagation of low energy particles in the interplanetary magnetic fields. Coupled with our measurements at higher energies they suggest that the typical quiet time peak differential intensity at $\approx$ 100 MeV is not likely to exceed 0.1/m^2-sec and could concievably be less than 0.01/m^2-sec at this energy - depending on the shape of the spectrum at the earth.

Finally we should like to remark regarding the limits on the intensity of solar neutrons vis-a-vis the limits on solar γ-rays in the 1-10 MeV range as recently reported by Peterson et.al. (1966).

In the absence of any active nuclear processes producing either energetic neutrons or γ-rays on the sun, an albedo flux of these particles from the sun would nevertheless be expected on the basis of the interactions of galactic cosmic rays in the solar atmosphere. An upper limit to this albedo flux may be obtained by following Peterson et.al. (1966) and assuming that the intensity of galactic cosmic rays at the solar atmosphere is equal to that over the polar regions of the earth. Consequently the albedo fluxes directly above the solar atmosphere and the earths atmosphere will be comparable as well. We estimate an albedo neutron flux $\approx 5/m^2$-ster-sec at 100 MeV over the poles at the earth-based on known albedo proton flux at this energy (Webber, 1966). The measured limit on solar neutrons at this energy is a factor of 25 below this. Since the sun subtends a solid angle $\approx 10^{-4}$ of a steradian at the earth, this measured intensity limit is still a factor $\approx$ 400 above the possible solar albedo source at the earth. Similar arguments can be invoked at other energies-taking into account the expected spectrum of albedo neutrons and their decay enroute to the earth. For example, the limit set by Roelof at 30 MeV is some 3×10^{-4} times the (upper limit) expected neutron albedo at the sun and therefore a factor of only 3 above this expected source limit at the earth.

In comparison to this, Peterson et.al. (1966), set a limit on the γ-ray flux from the sun at 1 MeV which is a factor $\approx$ 20 below the possible (solar) albedo flux at this energy at the sun-and consequently a factor of $\approx$ 500 above this expected source limit at the earth.

It would seem from the above discussion that the concensus of present neutron and γ-ray measurements is consistent with the sun playing a rather passive role in the production of high energy neutrons and γ-rays-at least at quiet times.

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References

Apparao, M.V. Krishna, R.R. Daniel, B. Vijayalakshimi, V.L. Blatt, "Evidence for the Possible Emission of High-Energy Neutrons from the Sun," J. Geophys. Res. 71, 1781, (1966).

Bame, S.J., and J.R. Asbridge, "A Search for Solar Neutrons Near Solar Minimum," J. Geophys. Res., 71, 4605, (1966).

Dorman, L.I., "Cosmic Ray Variations," State Publishing House for Technical and Theoretical Literature, Moscow, (1957).

Metropolis, N., R. Bivins, M. Storm, A. Turkevich, J.M. Miller and G. Freidlander, "Monte Carlo Calculations on Intranuclear Cascades," Parts I and II, Phys. Rev., 110, 185-219, (1958).

Ormes, J.F., and W.R. Webber, "Measurements of the Primary Proton and Helium Spectra and Their Modulations Using a Balloon-Borne Cerenkov-Scintillation Counter," Proc. Int. Conf. Cosmic Rays, London, 1, 349, (1965).

Peterson, L.E., D.A. Schwartz, R.M. Pelling, and D. McKenzie, "The Upper Limit Solar Gamma-Ray Spectrum to 10 MeV," J. Geophys. Res., 71, 5778, (1966).

Roelof, E.C. "Effect of the Interplanetary Magnetic Field on Solar Neutron-Decay Protons," J. Geophys. Res., 71, 1305-1318, (1966).

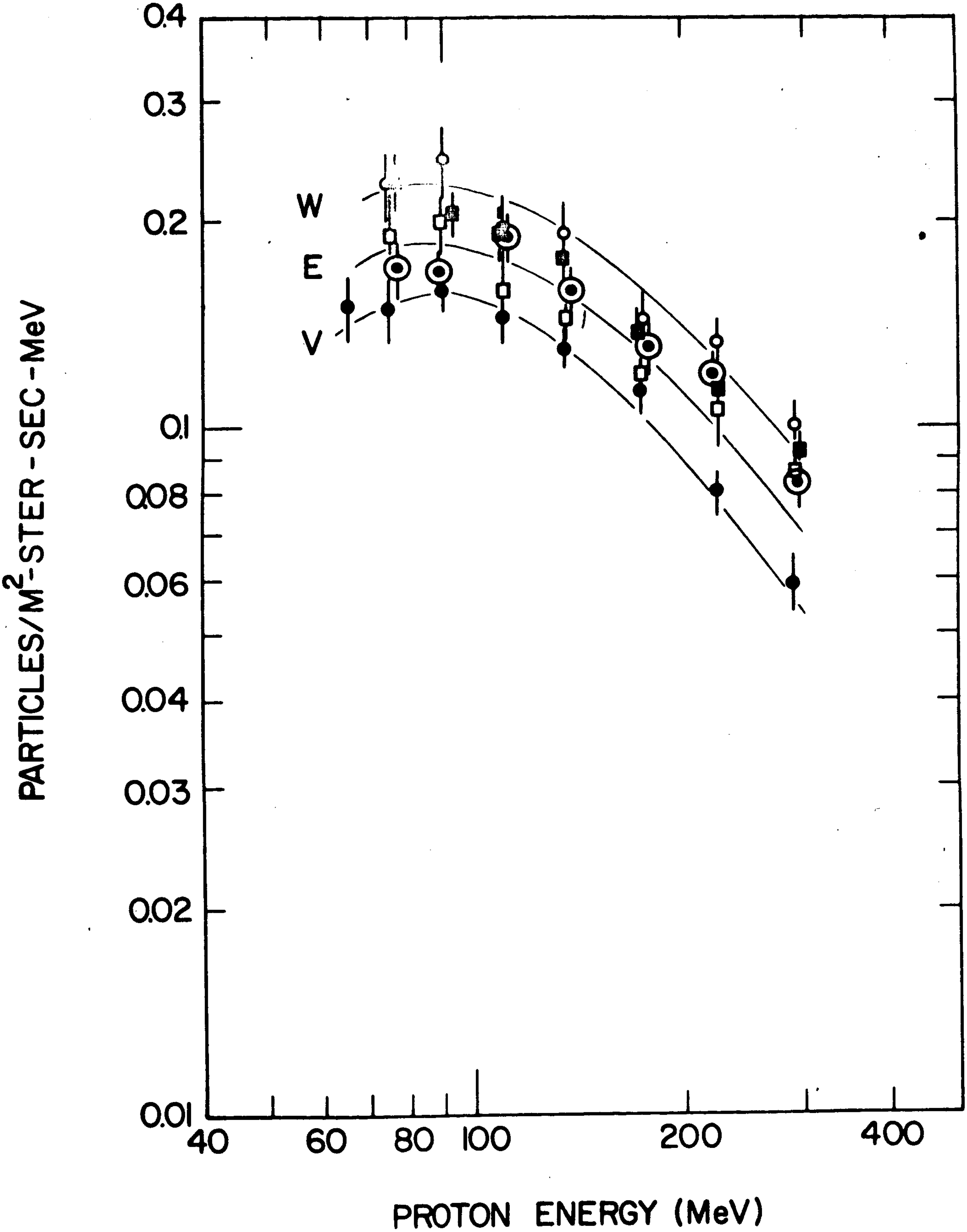
Webber, W.R., "The Spectrum and Charge Composition of the Primary Cosmic Radiation," Handb. der Physik, 46-2, 173, (1967), Springer-Verlag, Heidelberg.

Figure Captions

Figure 1 Differential intensities of secondary protons in the energy range 60-320 MeV measured at Tucuman, Argentina (P_c = 12.1 BV). Vertical flight (V), depth 9.2 g/cm^2 ●; Rotating flight, slant depth 12.9 g/cm^2, West (W) ○ ; East (E) □; North (N) ◆; South (S) □ .

Figure 2 Efficiency for production of secondary protons between 60 and 320 MeV at 12.9 g/cm^2 atmospheric depth as a function of primary proton (nucleon) energy.

Figure 3 Recent limits on the differential intensities of solar neutrons at the earth. (1) Bame and Asbridge (1966); (2) Apparao et.al. (1966); (3) Roelof, (1966). See text for explanation of results labeled "this paper."



PARTICLES/M²-STER-SEC-MeV
0.4
0.3
0.2
0.1
0.08
0.06
0.04
0.03
0.02
0.01
W
E
V
40
60
80
100
200
400
PROTON ENERGY (MeV)

FIG. 1

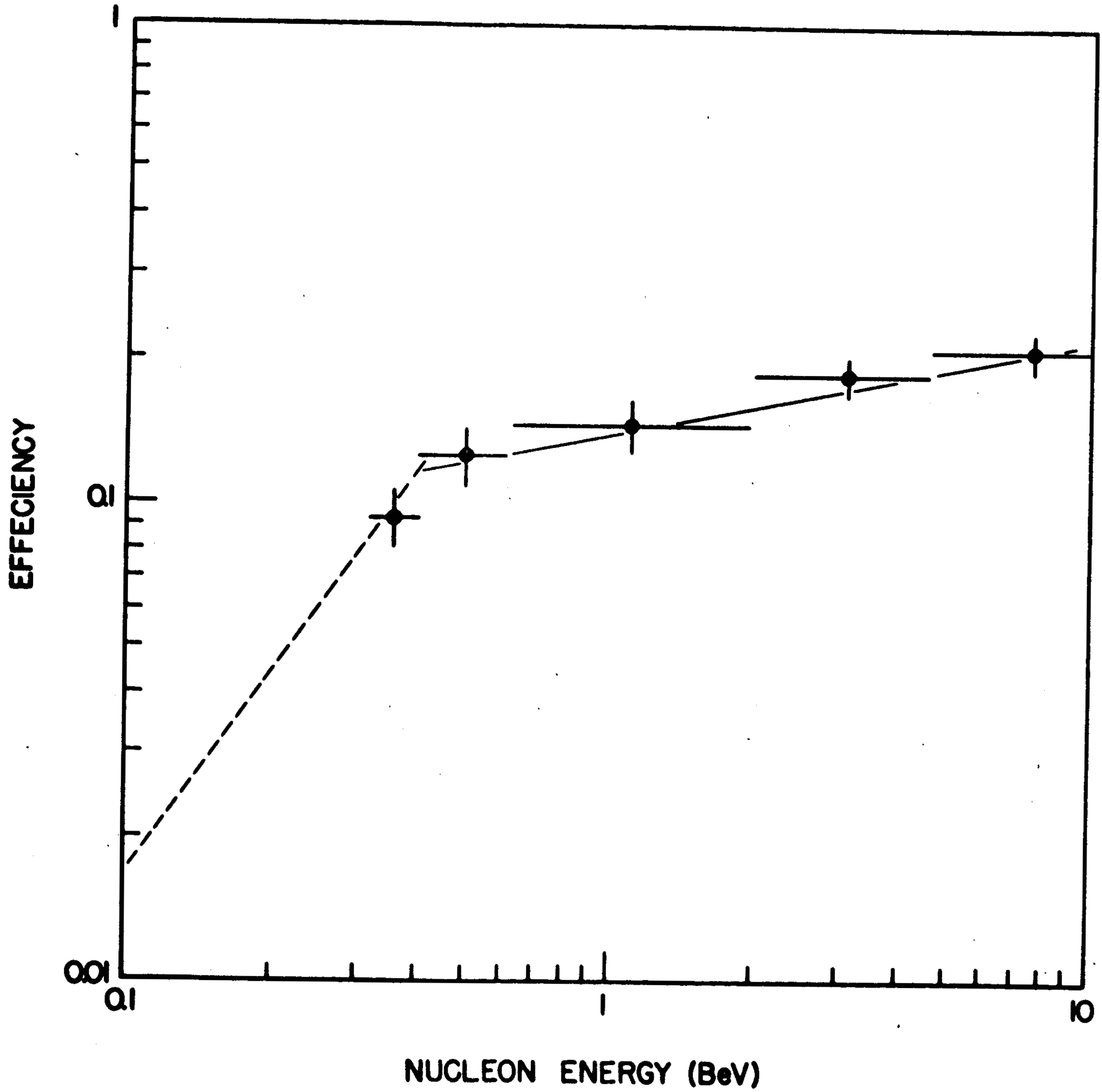
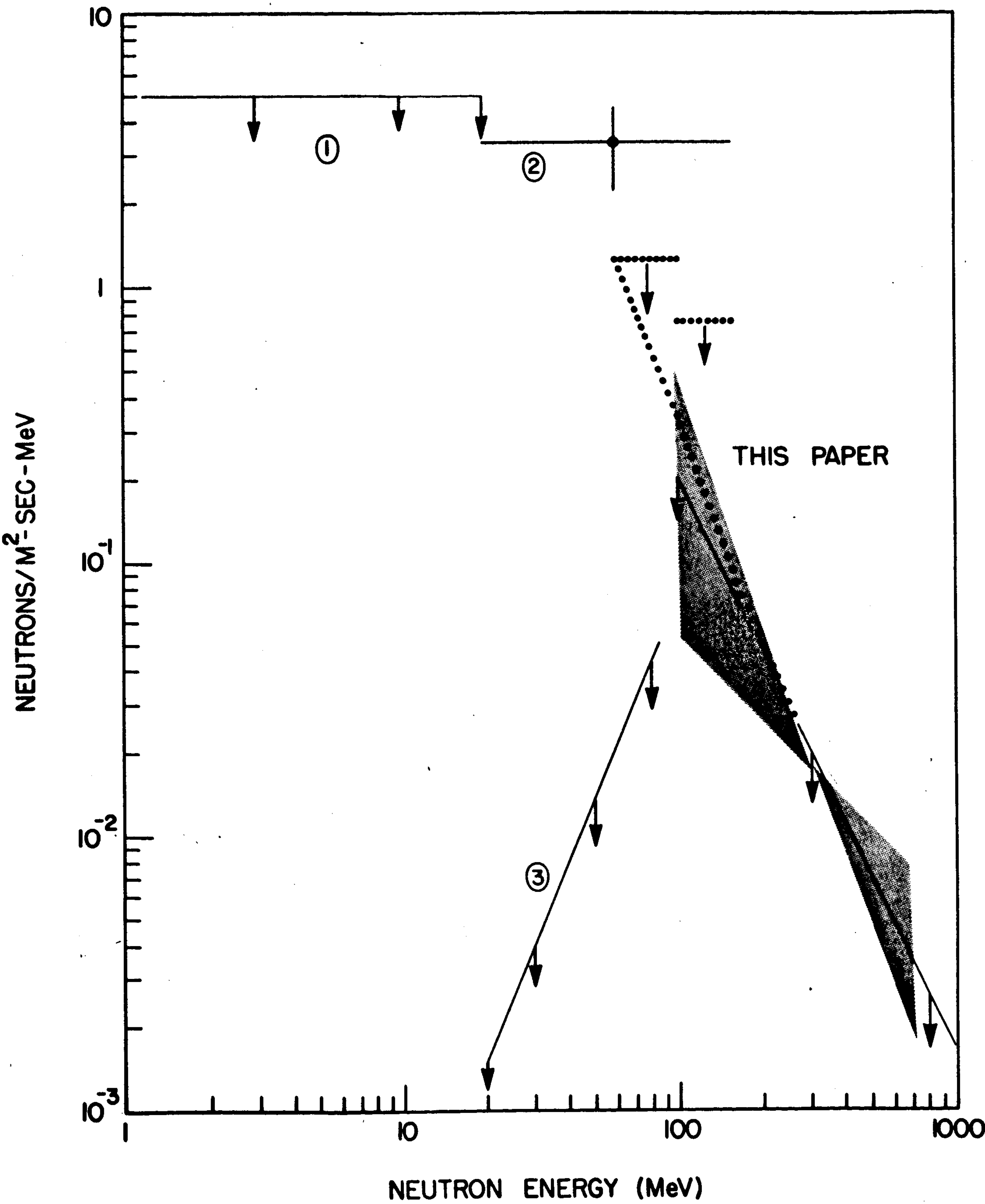


FIG 2



10
1
10^{-1}
10^{-2}
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NEUTRONS/M^2-SEC-MeV
1
10
100
1000
NEUTRON ENERGY (MeV)
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