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AN ESTIMATE OF THE PROMPT PHOTON SPECTRUM ARISING FROM COSMIC-RAY BOMBARDMENT OF THE MOON

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Abstract

An estimate has been made of the photon leakage spectrum from the moon due to photons arising from the capture and inelastic scattering of neutrons produced by galactic cosmic rays. The method of calculation consisted of estimating the energy and spatial distribution of the neutron flux in the moon and then using Monte Carlo methods to obtain the photon source and to perform the photon transport. While the photon production and transport are carried out with some exactitude, the results must be considered very approximate because of the approximate neutron-flux distribution that is used. In particular, no attempt is made to account for the important effect which hydrogen in the lunar composition would have on the neutron-flux distribution.

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I. INTRODUCTION

Measurement of the photon-energy spectrum from the moon by a lunar orbiting satellite has been carried out elsewhere [1] and, presumably, more complete measurements will be made in the future. The purpose here is to present an approximate calculation of some of the general features of the lunar photon spectrum produced by galactic cosmic-ray bombardment.

A complete description of the photon production would require a detailed calculation of the nucleon-meson cascade induced by the galactic cosmic-ray bombardment. Such detailed cascade calculations are not feasible at the present time because of the lack of data on particle production from high-energy nucleon-nucleus and alpha-particle-nucleus collisions. Here the neutron spectrum that would arise from the cosmic-ray bombardment of the moon was estimated in a very approximate manner and only the prompt photons arising from these neutrons are considered. Furthermore, because of the lack of photon-production data for high-energy neutron-nucleus collisions, only the photon-leakage spectrum contributed by prompt photons arising from low-energy (<18 MeV) neutron capture and inelastic-scattering interactions is determined in detail. An approximate calculation is made of the contribution of neutrons above 18 MeV and of the incident protons to the total prompt photon leakage.

In section II the procedure used for obtaining the photon-source distribution and for performing the photon-transport calculations is given. In section III the calculated photon leakage spectra for the three possible lunar compositions are presented and discussed.

II. METHOD OF CALCULATION

The neutron spectrum at several distances into the moon was constructed using the work of Arnold [2], Lingenfelter *et al.* [3], Newkirk [4], and Hess *et al.* [5]. These spectra are shown in Fig. 1. Also shown in Fig. 1 for comparison and later reference is the galactic proton spectrum [6]. The neutron spectra at 30 g/cm^2 and at 100 g/cm^2 for $E < 2$ MeV are based on Newkirk's calculations for the earth's atmosphere, and for $E > 2$ MeV these spectra are Arnold's estimate for a lunar composition.[2] At 0 g/cm^2 for $E < 2$ MeV the neutron-leakage spectrum calculated by Lingenfelter *et al.* was used, and for $E > 2$ MeV the shape was assumed to be the same as Arnold's 30 g/cm^2 spectrum. The shape of the 200 g/cm^2 spectrum for $E < 100$ MeV was based on the measurements of Hess *et al.* for the earth's atmosphere, and for $E > 100$ MeV the shape of Arnold's 100 g/cm^2 spectrum was used. The normalization of all spectra was based on estimates due to Arnold. The neutron spectrum at all spatial points, $\phi(E,x)$, was obtained by interpolation, and this estimate of $\phi(E,x)$ was assumed to be valid for all compositions. It must be understood, of course, that this neutron-flux distribution is very approximate and therefore the photon leakage calculated from it is also very approximate. In particular, no attempt is made to account for the important effect that hydrogen in the lunar composition would have on this distribution [3].

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[2] Arnold's spectra are not sensitive to the assumed lunar composition although the hydrogen content is assumed to be low [2].

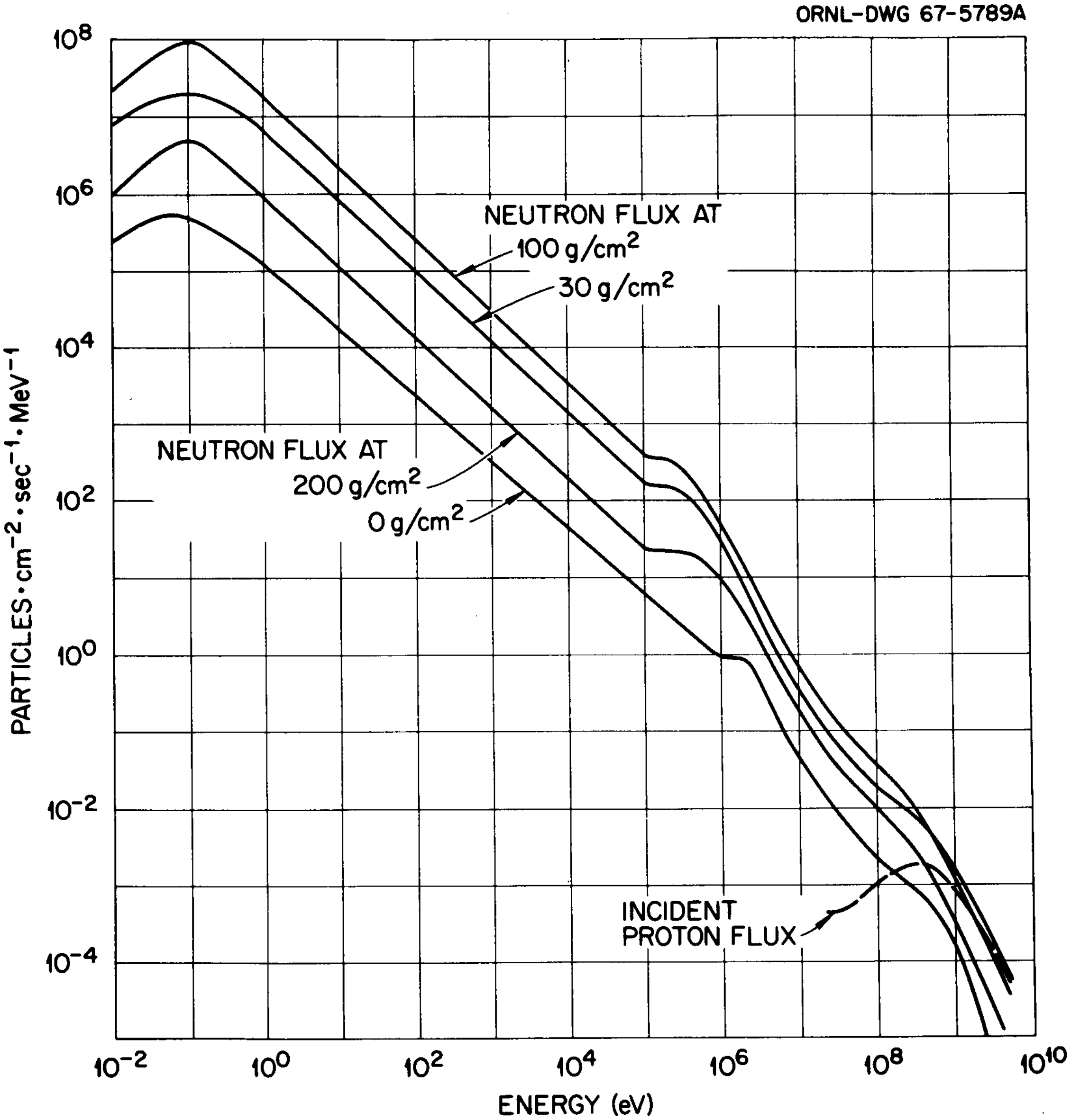

Fig. 1. Estimated Neutron Spectra in Moon Due to Cosmic Ray Bombardment; Incident Proton Flux.

The photon source strength can be expressed as

$$S(E',x) = \sum_{\ell} \sum_{k} \int_{E_{min}}^{E_{max}} dE\ \phi(E,x)\ \sigma_{\ell k}(E)\ \eta_{\ell k}(E \to E')\ , \qquad (1)$$

where

$S(E',x)$ = number of photons produced per unit energy at E' per unit volume at x per unit time

$\sigma_{\ell k}(E)$ = macroscopic neutron cross section at energy E for the kth type of interaction (capture or inelastic scattering) with the ℓth element

$\eta_{\ell k}(E \to E')$ = number of photons produced per unit energy at E', given that a neutron of energy E has kth type interaction with the ℓth element.

E_{max} is the maximum neutron energy to be considered and $E_{min} = 10^{-8}$ MeV. Because of the form of the data for $\eta_{\ell k}$ and since the photon source will be used as input to a Monte Carlo transport program, it is convenient to sample the above source distribution for discrete values of E' and x. For this purpose Eq. (1) can be rewritten as

$$S(E',x) = \sum_{k} \sum_{\ell} \int_{E_{min}}^{E_{max}} dE\ p_n(E,x)\ p_{\ell}(E)\ p_k(E)\ p_{\gamma}(E')\ W_1\ W_2(E)\ , \qquad (2)$$

where

$$p_n(E,x) = \phi(E,x)\ \sigma(E)/W_1$$

$$\sigma(E) = \sum_{\ell} \sum_{k} \sigma_{\ell k}(E)$$

$$W_1 = \int_{o}^{\infty} dx \int_{E_{min}}^{E_{max}} dE\ \phi(E,x)\ \sigma(E)$$

$$p_\ell(E) = \frac{\sigma_\ell(E)}{\sigma(E)}$$

$$\sigma_\ell(E) = \sum_k \sigma_{\ell k}(E)$$

$$p_k(E) = \sigma_{\ell k}(E)/\sigma_\ell(E)$$

$$p_\gamma(E') = \eta_{\ell k}(E \to E')/W_2(E)$$

$$W_2(E) = \int_0^\infty dE' \; \eta_{k\ell}(E \to E') \ .$$

Values of E' and x are then realized by sampling E and x from the joint probability density function $p_n(E,x)$, selecting k and ℓ according to the probabilities $p_k(E)$ and $p_\ell(E)$, respectively, and then choosing E' from $p_\gamma(E')$. Each source photon then has the statistical weight $W_1 W_2(E)$.

Selection of the source photon energy was accomplished using a computer program developed in a related study by Leimdorfer and Boughner [7]. Photon-production data for inelastic scattering (valid for neutron energies up to 18 MeV) were taken from the compilation of Ray *et al.* [8] for all elements used except magnesium. The magnesium data are the same as those used in [7]. The photon-production data for thermal-neutron capture were taken from the compilation of Bartholomew *et al.* [9] and Groshev *et al.* [9], and these same data were used for epithermal-neutron capture. Neutron cross sections were obtained from the O5R cross-section library [10].

The photons were transported using the OGRE Monte Carlo program [11]. The isotropic angular distribution of the source photons was biased (with appropriate modification to the photon weight) to encourage leakage and thereby improve the statistics of the calculation. The production and transport of annihilation photons were included. Photons below 0.3 MeV were not transported.

Plausible lunar compositions, which are consistent with different hypotheses of the moon's origin, have been inferred by Palm and Strom [12] and represented by three rock types: acidic, basaltic, and aerolitic.[3] The range of elemental abundances for each of these rocks is shown in Table 1. Calculations were performed for each type of rock (using a linear average for the abundance ranges shown in the table) with the exception that hydrogen was not included. The inclusion of relatively large amounts of hydrogen would, of course, alter the neutron spectra in Fig. 1 and could influence the photon leakage spectrum significantly. Also, the omission of hydrogen in the compositions means that the 2.2-MeV photon production from neutron capture in hydrogen is neglected. The density of the moon was taken to be 3.34 g/cm^3 [14].

Photon production due to inelastic scattering with the elements Ca, Na, Ni, S, and K was not included because of the scant photon-production data for these elements. The omission of these photons is not expected to be important since it is estimated that they would contribute only a few percent to the total photon production.

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[3] Preliminary analysis of the α-scattering data obtained from the recent Surveyor V mission suggests a basaltic-type composition at the landing site [13].

Table 1

Elemental Abundances, in Weight Percent, of Possible Lunar Compositions (from Palm and Strom [12])

Element	Acidic	Basaltic	Aerolitic
O	47 - 52	43 - 46	33 - 44
Si	31 - 38	21 - 24	17 - 25
Al	5 - 10	3.5 - 9	1 - 6
Fe	1 - 6	6.5 - 10	12 - 22
Mg	0.1 - 2	3 - 14	14 - 18
Ca	0.1 - 3	5 - 8	1 - 7
Na	0.2 - 4	1 - 2.5	0.6 - 0.8
K	1 - 5	0.2 - 1.5	0.1 - 0.2
Ni			0.1 - 1.7
S			0.2 - 2
H	0.07 - 0.2	0.1 - 1	0.03 - 0.1

III. RESULTS AND CONCLUSIONS

Photon leakage spectra based on neutron energies less than $E_{max} = 18$ MeV are shown in Figs. 2, 3, and 4 for the three assumed compositions. The width of the energy intervals for the histograms is 0.025 MeV, and the statistical error (one standard deviation) due to selection from the photon-source distribution and to the photon transport is indicated. The more prominent peaks are labeled according to the element and type of interaction producing the photon. The total photon leakage is 14, 12, and 9 photons per cm^2 per sec for the aerolitic, basaltic, and acidic compositions, respectively. The leakage spectra for all three compositions exhibit easily identified peaks that are well above the continuum. From the appearance of these spectra, one would expect the more prominent peaks to still be conspicuous after the smoothing effect of a detector response.

The magnitudes of the more prominent peaks for each composition are compared in Table 2. The corresponding peaks for each composition differ sufficiently in magnitude to identify the type of composition. For example, the ratio of the 7.63- and 7.64-MeV iron capture line to the 6.10-MeV oxygen inelastic line is about 0.5, 2, and 4 for the acidic, basaltic, and aerolitic compositions, respectively. The acidic composition is easily distinguishable by the prominence of the silicon lines.

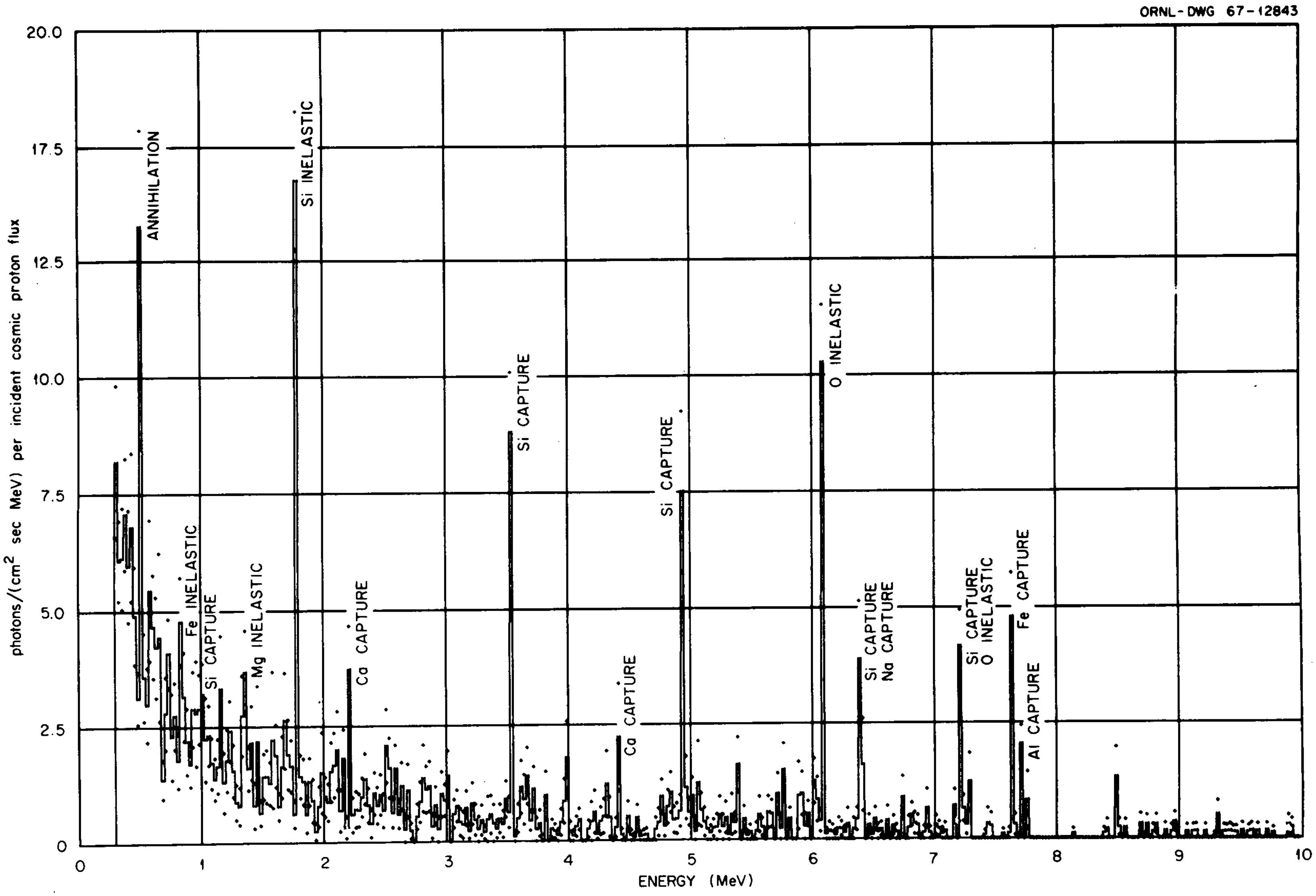

Fig. 2. Photon Leakage Spectrum from Lunar Surface for Acidic Composition.

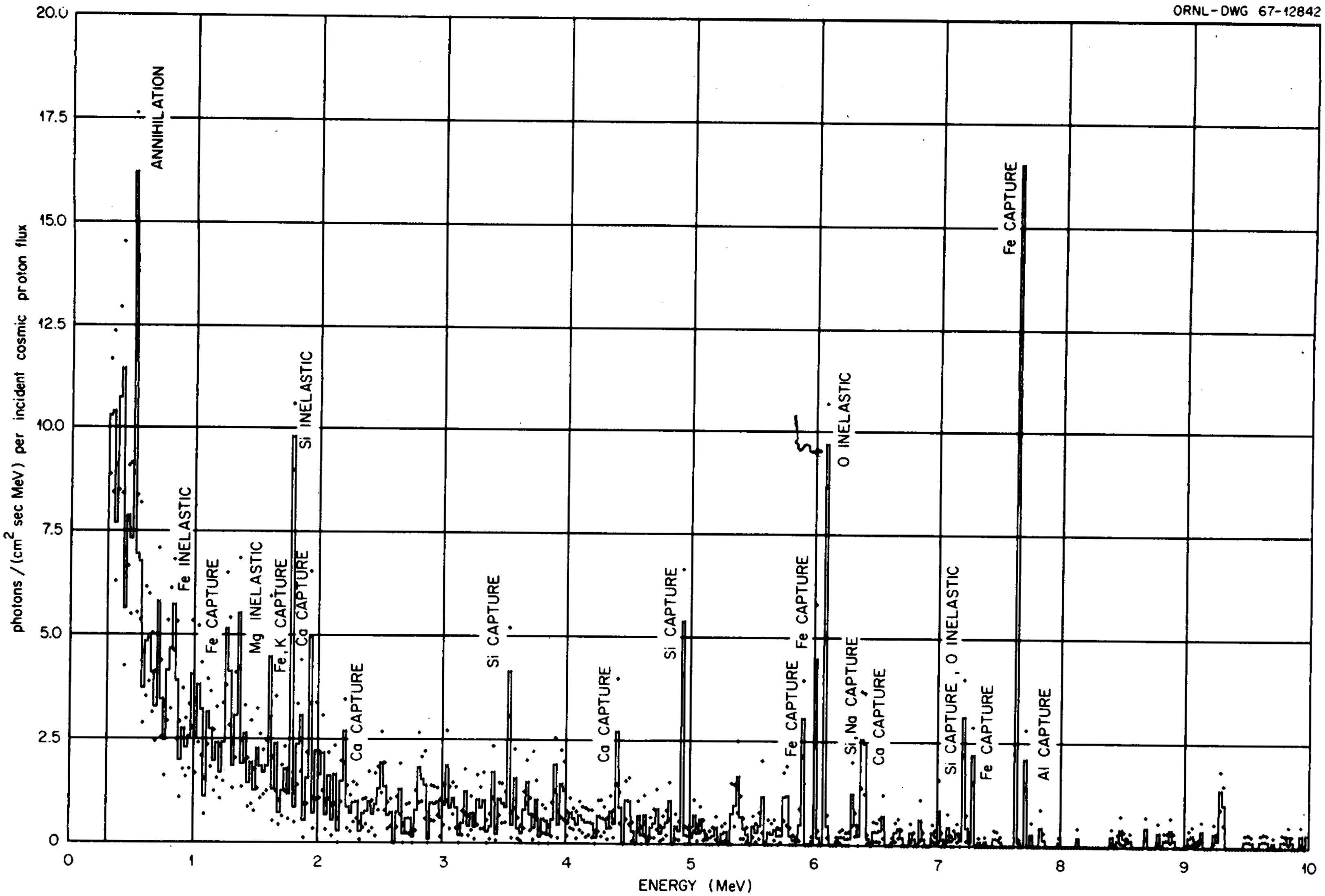

Fig. 3. Photon Leakage Spectrum from Lunar Surface for Basaltic Composition.

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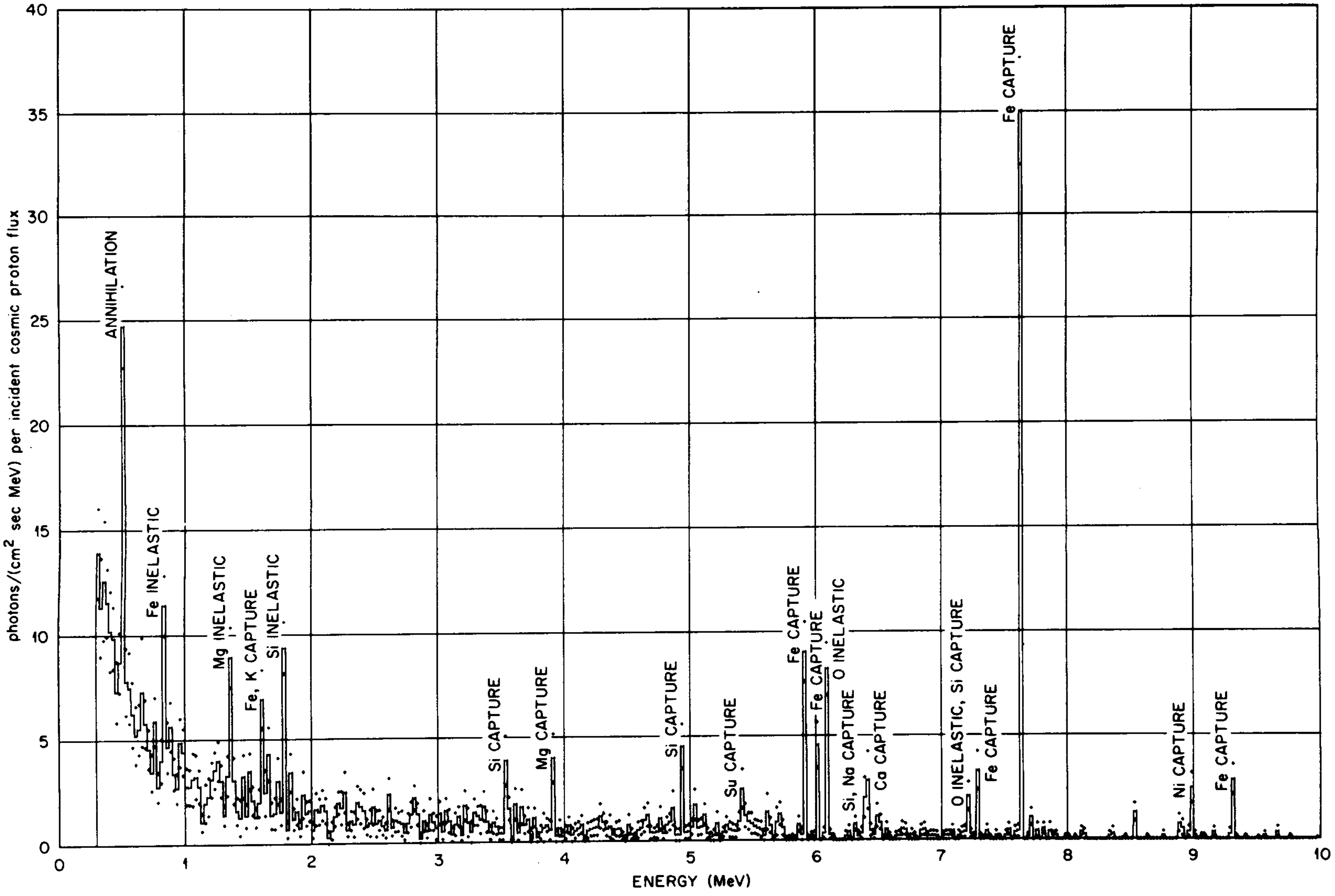

Fig. 4. Photon Leakage Spectrum from Lunar Surface for Aerolitic Composition.

Table 2

Comparison of the More Prominent Peaks in the Photon Leakage Spectrum

Energy Interval (MeV)	Interaction and Photon Energy (MeV)	Magnitude of Peak (Photons/cm^2·sec·MeV)		
		Acidic	Basaltic	Aerolitic
0.825 - 0.850	Fe inelastic, 0.85	4.8 ± 0.9	5.7 ± 1.1	11.4 ± 1.4
1.350 - 1.375	Mg inelastic, 1.37	3.7 ± 0.9	5.5 ± 1.3	8.9 ± 1.4
1.600 - 1.625	Fe capture, 1.61 K capture, 1.62	1.9 ± 0.7	4.5 ± 1.5	6.9 ± 1.4
1.775 - 1.800	Si inelastic, 1.78	14.3 ± 1.5	9.8 ± 0.8	9.4 ± 1.2
3.525 - 3.550	Si capture, 3.54	8.8 ± 1.3	4.1 ± 1.1	3.9 ± 1.2
4.925 - 4.950	Si capture, 4.94	7.5 ± 1.7	5.4 ± 1.3	4.5 ± 0.3
5.900 - 5.925	Fe capture, 5.92	1.0 ± 0.5	3.1 ± 0.9	9.0 ± 1.4
6.075 - 6.100	O inelastic, 6.10	10.3 ± 1.2	9.7 ± 1.0	8.2 ± 1.3
7.625 - 7.650	Fe capture, 7.64 Fe capture, 7.63	4.8 ± 1.0	16.5 ± 2.3	35.0 ± 2.6

Although the photon-production data are strictly applicable only for neutron energies of less than 18 MeV, an approximate calculation was made to include de-excitation photons produced by the interaction of neutrons above 18 MeV. For this rough estimate it was assumed that the photon-production spectrum for neutron energies greater than 18 MeV is the same as that at 18 MeV. The photon multiplicity for $E > 18$ MeV was based on experimental results for photon production in aluminum by high-energy protons [15]. A comparison of the total photon leakage from this approximate calculation using $E_{max} = \infty$ with the previous results for $E_{max} = 18$ MeV indicated that about 60% of the total photon leakage due to neutron interactions at all energies is contributed by neutrons with energies of less than 18 MeV. Furthermore, about 90% of the total photon leakage is contributed by neutrons with energies of less than 75 MeV.

It is of interest to compare the photon leakage calculated above due to prompt photon production by neutrons with the leakage contributed by prompt photons resulting from incident proton-nucleus interactions. An approximate calculation using the proton-source spectrum shown in Fig. 1 and the experimental photon-production data of Zobel *et al.* [15] for protons indicates that the proton contribution amounts to about 1% of that of the neutrons. This estimate does not include a contribution from incident protons below 20 MeV which are not shown in Fig. 1, but since protons of this energy have a very short range in matter they will predominantly slow down and stop without producing photons, and therefore this contribution is expected to be small. There will also be a contribution to the total photon leakage from photons produced by incident alpha particles, but since the number of incident alpha particles is small compared to the number of incident protons this contribution to the photon leakage may also be expected to be small compared to the contribution from neutrons.

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