

LUNAR NEUTRON CAPTURE RATES AND SURFACE MIXING OF THE REGOLITH,
Dorothy S. Woolum and D. S. Burnett, Division of Geological and Planetary
Sciences, California Institute of Technology, Pasadena, California 91109.

The Apollo 17 Lunar Neutron Probe Experiment (LNPE) (1) was performed in order to provide *in situ* lunar surface data on (a) the absolute rates of low energy neutron capture as measured in ^{235}U and ^{10}B targets, (b) the depth dependence of these rates down to 2 meters and (c) the neutron energy spectrum by measuring Cd absorption and by measuring the amounts of $^{80,82}\text{Kr}$ produced by neutron capture on $^{79,81}\text{Br}$ (data to be reported by Marti and co-workers). All of the above objectives were accomplished. Although we are in the last phases of data processing, the results on ^{10}B capture given here should be regarded as preliminary. However, the ^{235}U fission data have been completely analyzed.

Fission track densities from mica detectors at 8 different depths have been converted, using laboratory calibration data, into ^{235}U fission rates and the results are displayed on

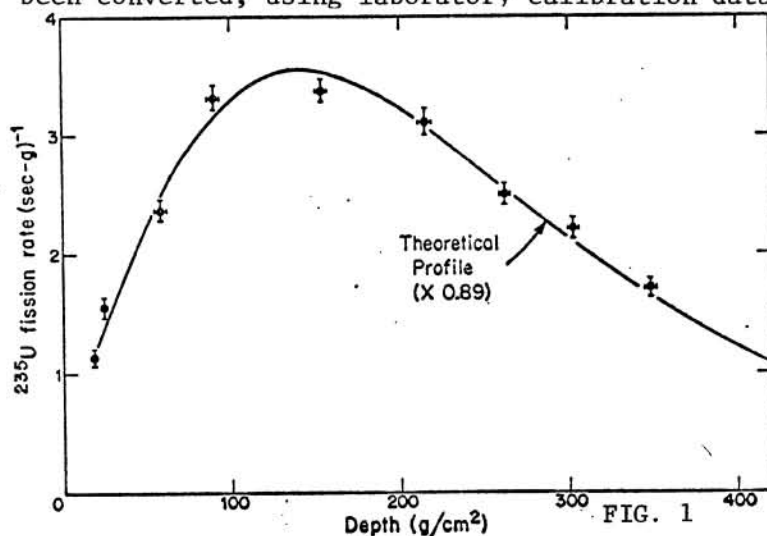


FIG. 1

Fig. 1. For comparison the theoretical fission rate profile of Lingenfelter *et al.*, (2) (LCH) multiplied by a factor of 0.89, is shown. No adjustment of the depth scale of the theoretical profile has been made. The LCH curve has been corrected for the difference in galactic cosmic ray intensity between the Apollo 17 mission and the average of the last solar cycle. The error bars on the data points indicate relative errors only. The uncertainty in the absolute fission rate scale is about $\pm 10\%$ (standard deviation); consequently, there is good agreement between the depth dependence of the theoretically predicted and experimentally obtained fission rate profiles.

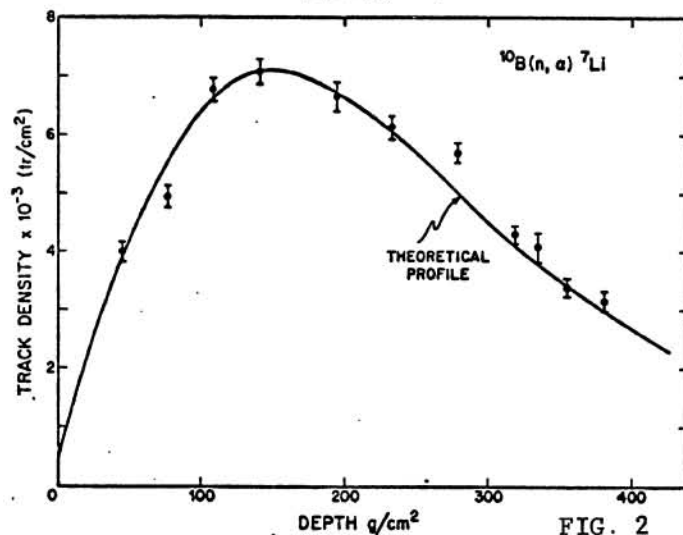


FIG. 2

Figure 2 shows the depth dependence of track densities in TN cellulose triacetate plastic which was exposed to the ^{10}B targets. No corrections have been applied to the data as yet and the errors are one standard deviation calculated purely from

Neutron Capture Rates

Woolum, D. S., et al.

counting statistics. In this case, we have normalized the theoretical capture rate profile to the data point at 140 g/cm^2 , near the peak in the profile. The shape of the theoretical profile is a reasonable description of the trend of the data points. There is more scatter in the data than was the case for the ^{235}U . Some of the scatter may represent variations in the efficiencies of individual detector positions, for which corrections have not yet been applied, but it also in part reflects difficulties in long term counting reproducibility of the short, low density tracks in the plastic detectors. Nevertheless, the correspondence of the shapes of the experimental and theoretical profile indicates that the depth variation of lunar neutron capture rates is relatively well known for the purpose of interpreting lunar sample data.

Based on calibration data, the absolute ^{10}B capture rate is about 2/3 of that calculated by LCH. Additional data processing will be carried out to check this preliminary result but the difference in the experimental and theoretical rates, although not large, appears to be significant. Our final accuracy in the measured ^{10}B capture rate should be significantly better than $\pm 15\%$ (standard deviation). For comparison, the ^{235}U fission rate at the same depth is $0.89 \pm .11$ of the theoretical value and the ^{60}Co activity reported by Wahlen *et al.*, (3) corresponds to $0.67 \pm .24$ of the theoretical value. The uncertainty in the absolute normalization of the theoretical calculations was estimated as $\pm 30\%$ by LCH so the overall agreement in all experimental capture rates is good although at this stage the data suggest that capture rates which are slightly ($\sim 20\%$) lower than the theoretical values should be adopted.

The LNPE contained cylinders of Cd surrounding ^{10}B --TN detectors at 180 and 370 g/cm^2 . Cd strongly absorbs neutrons below about 0.5 eV; thus, as shown in Figure 3, a decrease in track density (ρ) is observed underneath the Cd compared to the track density (ρ_0) outside. The equivalent attenuation measured for a well-thermalized neutron flux is shown for comparison. The attenuation is much smaller for the lunar data, graphically illustrating the expected non-thermal shape of the low energy lunar neutron spectrum which is due to the significant abundances of low energy neutron absorbers in the lunar materials (Fe, Ti, REE, etc.). The lunar (ρ/ρ_0) ratio can be used to calculate a "Cd ratio" of the total density (n/cc) of neutrons (for energies from 0 to ~ 10 eV) to the density above 0.5 eV. Cd ratios of 2.1 ± 0.2 and 2.7 ± 0.4 at 180 and 370 g/cm^2 , respectively are obtained, which can be compared to the theoretical values of 2.7 and 2.9 at similar depths. Although the experimental ratios require further confirmation, it appears that: (a) the LCH spectrum has an excess of low energy neutrons, as also inferred from the relative capture rates of ^{149}Sm and ^{157}Gd in lunar samples (4), and (b) the increase in the fraction of neutrons below 0.5 eV with increasing depth may be somewhat larger than predicted theoretically.

The overall good agreement between the LNPE results and the LCH calculations shows that lunar neutron capture processes are relatively well understood and that previous interpretations of the neutron capture data obtained from lunar samples should be reliable. Because of differences in the actual and theoretical energy spectra, additional consideration must be given to the uncertainties in the critical ^{157}Gd capture rate which is quite sensitive to the shape of the spectrum below 0.2 eV. It is still possible that the LCH

Neutron Capture Rates

Woolum, D. S., et al.

capture rate for ^{157}Gd may be high by as much as 40%, although even a change of this amount would not drastically alter previous conclusions.

As discussed previously (e.g., 5) neutron fluences calculated for surface soils from Gd isotopic data are low compared to those expected for a well-mixed regolith using regolith depths reported from field observations or active seismic data. Our results show that this "neutron deficit" cannot be due to inaccuracies in the theoretical capture rate profiles used previously. Either (a) the regolith has not been uniformly mixed over a 10^9 yr time scale and progressively more irradiated material is located at the base of the regolith than at the surface, (b) the average cosmic ray flux striking the lunar surface was less in the past 10^9 yr than at present by a factor of 2-3, or (c) the regolith depths inferred from field or seismic data are low by factors of 2-3. Alternative (a) is reasonable if most of the Gd found in surface soils is the result of a relatively recent (within $\sim 10^9$ yr) deposition of previously unirradiated (preferably Gd-rich) material and has only been mixed through the upper few meters. The similarity of the required properties of the deposit to those of Apollo 12 KREEP make this model attractive for this site, but it is then puzzling why the fluences are similar for surface soils from all missions. This similarity can be explained if the depth through which the Gd-rich surface deposit has been mixed by subsequent small scale impacts is correlated with the time of deposition, i.e., older deposits have been mixed deeper. A ratio of depth of mixing to deposition time (i.e., a "surface mixing rate") of ~ 1 meter/300 my can account for the observed fluences.

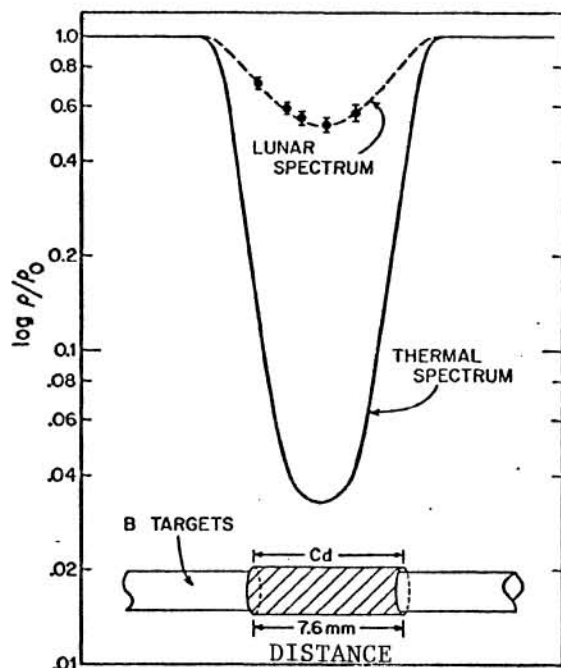


FIG. 3

References

- (1) Woolum, D.S., Burnett, D.S., Bauman, C. A., Apollo 17 Prelim. Sci. Report, NASA SP, in press, 1974; also Earth. Planet. Sci. Lett. in press, 1974.
- (2) Lingenfelter, R. E., Canfield, E. H., & Hampel, V. B., Earth. Planet. Sci. Lett., **16**, 355, 1972.
- (3) Wahlen, M., Finkel, R. C., Imamura, M., Kohl, C. P., & Arnold, J. R., Earth Planet. Sci. Lett., **19**, 315, 1973.
- (4) Russ, G. P., Burnett, D. S., Lingenfelter, R. E., Wasserburg, G. J., Earth. Planet. Sci. Lett., **13**, 53, 1971.
- (5) Russ, G. P., Earth Planet. Sci. Lett., **19**, 275, 1973.