Coo-1167-7

A Facsimile Report

Reproduced by
UNITED STATES
ATOMIC ENERGY COMMISSION
Division of Technical Information
P.O. Box 62 Oak Ridge, Tennessee 37830

29
SQT-63486R

EVIDENCE FOR SOLAR FLARE PROTON INDUCED RADIOACTIVITY IN LUNAR SURFACE MATERIAL RETURNED BY APOLLO 11

Values for the abundances of several radionuclides in eight lunar surface samples returned by the Apollo 11 mission have recently been reported by the Preliminary Examination Team (PET) (1). PET has emphasized the preliminary nature of their experimental results and, thus, our conclusions therefrom must necessarily be of a tentative nature also.

One approach to a consideration of these radionuclide results is to compare them with analogous data from stone meteorites. In Table 1 are listed several of the nuclides reported by PET in order of increasing half-life. For each of these, average specific radioactivities in lunar surface material and in typical stone meteorites (2), as well as the ratios of these two quantities, are given. Also listed are the types of nuclear reactions by which they may have been formed. Corresponding to each reaction, there is presented in the last column of Table 1 the ratio of the specific radioactivities after dividing each by the amount of target element in the sample (1,3). This corrected ratio should be close to unity if the same spectrum and intensity of particles incident on both the lunar surface and the meteorites are responsible for the reaction being considered. It should be borne in mind that, if the relative importance of a given reaction varies greatly between the two classes of materials, the value of this ratio may not be very meaningful.

Perhaps the most striking feature of the PET results is the rather high average Co^{56} content (≈ 31 dpm kg^{-1}). This Co^{56} (half-life = 77 d), as are most of the other radioactive species reported, is the result of the interaction of energetic particles in space with the lunar surface material, a phenomenon well known from studies of meteorites and recovered satellites (recent reviews are listed under 4). However, the reported specific activity of the Co^{56} in the material returned by Apollo 11 is a factor of two higher than typical radiochemically determined values in stone meteorites. Iron is by far the most likely element from which this nuclide is produced in these two classes of materials. Taking Harleton as a model stone metoerite, the Co^{56} content of the lunar surface materials per unit weight of iron (1,3) is high by a factor of about four. The average specific radioactivity of none of the other species reported by PET is as disparate from that observed in stone meteorites, if differences in the amounts and possible nature of the target material involved in their production are kept in mind.

For example, the comparable specific radioactivities of Sc^{46} in lunar material and in stone meteorites presumably arise from the presence of the appreciable amount of titanium in the former (1,5), which compensates as target material for the lower iron abundance. The lower amount of Mn^{54} is probably due to the lower iron content in the Apollo 11 samples (the principal nuclear reactions leading to Mn^{54}, again, include iron as the target). The lower lunar Na^{22} content is probably partly due to the lower sodium and magnesium abundances, while the larger amont of Al^{26} found in the lunar surface material is consistent with the higher aluminum abundance therein (1,3). Thus, the apparant inversion of

the Na^{22}/Al^{26} ratio (which is normally observed as greater than unity in stone meteorites (6)) may be due to the relative target abundances in the two classes of materials.

A reasonable explanation for the clear excess of Co^{56} in the lunar material is production of this nuclide by particles from the solar flare of 12 April 1969. This flare was accompanied by the presence of a very great excess of energetic protons in space for a period of several days, with no major events occurring between this one and the collection of the Apollo 11 samples. The integral flux of these interplanetary solar flare protons is estimated at about 10^9 cm^{-2} for the 10 to 100 MeV energy range on the basis of data from the IMP-4 satellite (7). Protons in this energy range are particularly effective in producing (p,n) nuclear reaction products (such as Co^{56}) in high specific radioactivity close to the surface of exposed material. They are not as effective in increasing the abundances of the other radionuclides listed in Table 1 under the conditions which prevailed for the Apollo 11 material. Using experimental values for the cross section of the $Fe^{56}(p,n)Co^{56}$ reaction (8), the abundance of iron in the Mare Tranquillitatis material (1), and an approximate energy spectrum for the solar flare particles (7), a simplified calculation gives an average of nearly a hundred dpm kg^{-1} of Co^{56} in the first two cm of depth of lunar material due to the flare. Since the activity induced by these particles will depend rather strongly on the actual depth from which the samples were obtained and the local topography, as well as on the applicability of the flare intensity experienced by IMP-4 to that on the Mare Tranquillitatis, quantitative agreement is not to be expected. The calculated amount, however, appears to be more than adequate to explain the excess Co^{56} observed (9).

More detailed conclusions must await the promised refinement of the PET results and, hopefully, data on more radionuclides from the Apollo 11 rocks and from rocks collected at different times in the solar cycle, as well as more rigorous estimates of the abundances expected to be produced in lunar materials by projectiles of various types.

H. R. Heydegger

Enrico Fermi Institute
The University of Chicago
Chicago, Illinois 60637

Anthony Turkevich

Enrico Fermi Institute and
Department of Chemistry
The University of Chicago
Chicago, Illinois 60637

Table 1. Comparison of Specific Radioactivities Observed in Apollo 11

Stone Meteorites

Nuclide	Half-life	Observed Specific Radioactivities ($dpm\ kg^{-1}$) Average Lunar Samples[a]	Typical Stone Meteorites[b]	Ratio (lunar/stone)	Possi[illegible] Nucle[illegible]
Co^{56}	77 d.	31 ± 4	14 ± 2	2.2 ± 0.4	Fe^{56} (
Sc^{46}	84 d.	11 ± 1	12 ± 1	0.9 ± 0.1	Ti^{46} + Ti^{48} Fe^{56}

Mn^{54}	312 d.	29 ± 5	72 ± 7	0.40 ± 0.08	Cr^{54}
					 Mn^{55} {
					 Fe^{56} {

Na^{22}	2.6 y.	43 ± 4	80 ± 8	0.54 ± 0.08	Na^{23} {
					 Mg^{24} {
					 Si^{28} {

Al^{26}	$7.4x10^5$ y.	80 ± 7	64 ± 6	1.3 ± 0.2	Mg^{26} Al^{27} { Si^{28}

a. Values from References item (1).

BLANK PAGE

…ioactivities Observed in Apollo 11 Lunar Material and in …e Meteorites

…pm kg^{-1}) …ical Stone …teorites^{b}	Ratio (lunar/stone)	Possible Nuclear Reactions	Ratio (lunar/stone) corrected for target abundance
± 2	2.2 ± 0.4	Fe^{56}(p,n)	4.3 ± 0.8
± 1	0.9 ± 0.1		
		Ti^{46}+Ti^{48} {(p,xpyn), (n,xpyn)}	0.012 ± 0.002
		Fe^{56} {(p,6p5n), (n,5p6n)}	1.8 ± 0.2
± 7	0.40 ± 0.08		
		Cr^{54} (p,n)	0.36 ± 0.07
		Mn^{55} {(p,pn), (n,2n)}	0.29 ± 0.06
		Fe^{56} {(p,2pn), (n,p2n)}	0.79 ± 0.16
± 8	0.54 ± 0.08	Na^{23} {(p,pn), (n,2n)}	0.96 ± 0.14
		Mg^{24} {(p,2pn), (n,p2n)}	1.6 ± 0.2
		Si^{28} {(p,4p3n), (n,3p4n)}	0.48 ± 0.07
± 6	1.3 ± 0.2	Mg^{26} (p,n)	3.8 ± 0.5
		Al^{27} {(p,pn), (n,2n)}	0.24 ± 0.03
		Si^{28} {(p,2pn), (n,p2n)}	1.1 ± 0.2

References and Notes

1. Lunar Sample Preliminary Examination Team, Science 165, 1211 (1969).
2. M. Honda and J. R. Arnold, Science 143, 203 (1964); J. P. Shedlovsky, P. J. Cressy, and T. P. Kohman, J. Geophys. Res. 72, 5051 (1967).
3. R. S. Clarke, Jr., Unpublished data (1964).
4. M. Honda and J. R. Arnold, in Handbuch der Physik (Springer, Berlin, 1967); T. P. Kohman and M. L. Bender, in High Energy Nuclear Reactions in Astrophysics, (Benjamin, New York, 1967).
5. A. L. Turkevich, E. J. Franzgrote, and J. H. Patterson, Science 165, 277 (1969).
6. See, for example, K. Fuse and E. Anders, Geochim. Cosmochim. Acta 33, 653 (1969); E. L. Fireman, Ibid. 31, 1691 (1967).
7. The authors are indebted to K. C. Hsieh and Prof. J. A. Simpson and his group for making available their preliminary data from IMP-4. Any errors in the interpretation of these data are, of course, the responsibility of the current authors.
8. S. Tanaka and M. Furkawa, J. Phys. Soc. Japan 14, 1269 (1959); I. R. Williams and C. B. Fullmer, Phys. Rev. 162, 1055 (1967).
9. It is important to bear in mind that the orientation of a large sample relative to the detectors may have a significant effect on the result for a radionuclide which is not homogenously dispersed throughout that sample, as would be the case for the solar particle induced reaction discussed here.

10. This work was supported by grants from the U. S. Atomic Energy Commission and the U. S. National Aeronautics and Space Administration.

Abstract. A comparison of the specific radioactivity values reported for lunar surface material from the Apollo 11 mission with analogous data for stone meteorites suggests that energetic particles from the solar flare of 12 April 1969 may have produced most of the Co^{56} observed.