COSMIC RAY EXPOSURE HISTORY OF LUNAR METEORITE EET87521 ; K. Nishiizumi[1], J. R. Arnold[1], P. Sharma[2], P. W. Kubik[2], J. Klein[3], and R. Middleton[3], (1) Dept. of Chemistry, Univ. of California, San Diego, CA 92093-0317, (2) Nuclear Structure Research Lab., Univ. of Rochester, Rochester, NY 14627, (3) Dept. of Physics, Univ. of Pennsylvania, Philadelphia, PA 19104

Lunar meteorites are expected to have complex cosmic ray exposure histories. They have been exposed both at some depth on the moon (2π irradiation) before their ejection and as small bodies in space (4π irradiation) during transportation from the moon to the earth. Their terrestrial age can also be long, similar to other Antarctic meteorites. Measurement of cosmogenic nuclides can provide essential constraints for these ages and help to unravel the complex history of these objects. This complexity requires measurement of three or more cosmogenic nuclides in the same sample.

We report here cosmogenic ^{36}Cl ($t_{1/2} = 3.0x10^5$ years) and ^{10}Be ($1.5x10^6$ years) results in lunar meteorite EET87521. The ^{36}Cl result was determined by the University of Rochester tandem accelerator [1] and the ^{10}Be result was determined by the University of Pennsylvania tandem accelerator [2]. The results are shown in Table 1 along with an ^{26}Al ($7.05x10^5$ years) datum (personal communication by G. Herzog). The cosmogenic radionuclide concentrations in EET87521 are the lowest among 9 lunar meteorites so far measured. Although three nuclides do not provide enough information to fully explain the complex history of this meteorite, our results do constrain the system.

The depth profiles of ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn have been measured in the Apollo 15 deep drill core [3, 4, 5, 6]. These observed profiles can be used to derive the exposure histories of lunar meteorites. Since the target chemical composition of EET87521 is relatively similar to that of the Apollo 15 drill core, the observed cosmogenic radionuclide concentrations in the meteorite can be compared to those in the core with minor modifications, using the Reedy-Arnold model [7]. We find that we must extrapolate the observed lunar core profiles toward greater depth because the concentrations of nuclides in EET87521 are much lower than those at the bottom of the core. Low cosmogenic nuclide concentrations can be explained by deeper ejection depth on the moon and short 4π exposure time (short moon-earth transition time).

The most probable scenario is that all significant cosmic ray exposure took place at a depth of 560-590 g/cm^2 in the lunar surface, and that the transition time to the earth (4π exposure) was very short, $<10^4$ years. The ^{36}Cl concentration is a little lower than expected for zero terrestrial age, permitting a terrestrial age for EET87521 of $<6x10^4$ years.

The other possible scenario is that the meteorite was ejected from very deep in the moon and all cosmogenic nuclides were produced in space (4π irradiation). Required exposure ages (transition times) are different for each nuclide (^{36}Cl age = $2.3x10^4$ years, ^{10}Be age = $6.7x10^4$ years, and ^{26}Al age = $3.7x10^4$ years). The discrepancy can be explained on this model by a long terrestrial age. The three nuclide concentrations are in fair agreement with a transition time of $(7\pm1)x10^4$ years and a terrestrial age of $5x10^5$ years. This terrestrial age is the longest among the measured Elephant Moraine meteorites but is not unreasonable [8]. Although some combinations of 2π and 4π models are possible, useful discussions are not possible until other cosmogenic nuclides such as ^{41}Ca, ^{53}Mn, and noble gases have been determined. For any possible model, the ejection depth must have been deeper than 560 g/cm^2 and the transition time was less than $8x10^4$ years.

Table 1. ^{36}Cl and ^{10}Be results in EET87521

	^{36}Cl (dpm/kg meteorite)	^{10}Be (dpm/kg meteorite)	^{26}Al* (dpm/kg meteorite)
EET87521,48	0.875 ± 0.052	0.666 ± 0.034	3.4 ± 0.2

* personal communication from G. Herzog

The exposure histories of 9 lunar meteorites (6 independent cases) are summarized in Table 2. Five out of six lunar meteorites were ejected from relatively shallow depths (few cm to about 3 m) and their transition times from the moon to the earth were all short (much shorter than $1x10^5$ years). The impact events seem to have occurred within the last 10^5 years for four lunar meteorites and $3x10^5$ years ago for one.

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In an early Monte Carlo model [9], the dynamics of meteorites of lunar origin were simulated. According to this analysis, on the assumption that objects ejected from the moon escape the earth's gravity field, roughly half of those reaching the earth have transit times less than 10^6 years. The nature of the model did not allow an estimate of the fraction with 4π exposure $<10^5$ years, but a rough fraction might be 15-20 %. This does not seem consistent with what we see.

Our preferred explanation is that some, perhaps most, of the objects we see did not escape from the earth-moon system upon ejection, and hence were captured very quickly by the earth. The escape velocity of an object from the earth's field near the moon, after it has left the moon's own gravity field (escape velocity 2.3 km/s) is about 1.4 km/s. With a steeply falling distribution of ejection velocities from the lunar surface, a remaining velocity of this order or less does not seem improbable, especially if the direction of ejection is retrograde to the moon's orbital motion. Motion of a small body in the earth-moon system should be unstable on a short time scale, because of the relatively close (1/81) mass ratio of the two main bodies, and their large diameter as compared to the dimensions of a bound orbit. Hence the transition time should be very short.

Alternatively, a single collision on the moon, for example just 10^5 years ago, might give rise to a group of "quick falls" even among the objects that initially escaped the earth's field. This explanation of the data seems less promising, however. Among the five short-lived objects in the present data set there seem to be at least three different ejection events represented, MAC88104-105, Y-791197, and Y-793274, with the other two offering more than one choice.

It is interesting that the all possible Martian (SNC) meteorites were ejected from depths in the parent body too great to yield observable cosmogenic nuclide production. One lunar meteorite (Y-82192, 82193, and 86032 pair) was ejected from below cosmic ray interaction depth on the moon and stayed in space about 11 million years. The case reported here, EET87521, is the second for which this possibility exists, though here we favor observable 2π production.

We wish to thank G. Herzog for providing the ^{26}Al result in EET87521 prior to the publication.

Table 2. Exposure histories of lunar meteorites

	Ejection Depth (g/cm^2)	Moon-Earth (My)	Terrestrial Age (My)	Reference
ALHA81005	150-175	<0.05	0.04-0.09	[10]
EET87521	560-590	<0.07	<0.06	This work
MAC88104 MAC88105	350-380	0.05	0.25	[10]
Y-791197	4-5	<<0.1	0.03-0.09	[10]
Y-793274	140-180	<0.02	<0.02	unpublished
Y-82192 Y-82193 Y-86032	>1000	11	0.08	[11, 12]

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