History of Meteorites from the Moon Collected in Antarctica

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In large asteroidal or cometary impacts on the moon, lunar surface material can be ejected with escape velocities. A few of these rocks were captured by Earth and were recently collected on the Antarctic ice. The records of noble gas isotopes and of cosmic ray–produced radionuclides in five of these meteorites reveal that they originated from at least two different impact craters on the moon. The chemical composition indicates that the impact sites were probably far from the Apollo and Luna landing sites. The duration of the moon-Earth transfer for three meteorites, which belong to the same fall event on Earth, lasted 5 to 11 million years, in contrast to a duration of less than 300,000 years for the two other meteorites. From the activities of cosmic ray–produced radionuclides, the date of fall onto the Antarctic ice sheet is calculated as 70,000 to 170,000 years ago.

IT IS NOW GENERALLY ACCEPTED THAT MOST METEORITES come from asteroids, but eight meteorites collected by Japanese and U.S. expeditions in Antarctica have been identified as rocks ejected from the moon by asteroid or cometary impact. Meteorite ALH A81005 was found in 1982 by a U.S. expedition in the Allan Hills region of Victoria Land. It was the first meteorite recognized to be of lunar origin (*1*). Subsequently, another seven meteorites were discovered to be of the same type, all of them collected on Antarctic ice: Y-791197 (Yamato Mountains), Y-793274, Y-82192, Y-82193, Y-86032, MAC 88104 (MacAlpine Hills), and MAC 88105. The largest meteorite from the moon found so far is MAC 88105, weighing 662 g, as compared to masses of 643 g for Y-86032 and less for the other lunar meteorites. So far, five lunar meteorites have been distributed for laboratory study (Table 1).

The study of the lunar meteorites contributes to a comprehensive knowledge of the lunar surface composition. The samples returned by the Apollo and Luna missions fall within a relatively small central nearside region of the moon covering only about 5% of the lunar surface. New data from lunar meteorites are thus essential for improving models for the chemical composition of the bulk moon. Furthermore, that material ejected from the moon (escape velocity 2.4 km/s) can reach Earth makes it plausible that the planet Mars, with an escape velocity of 5.0 km/s, is a source of certain meteorite classes such as the shergottites, nakhlites, and chassignites (*2*).

The formation history of the rock material in the lunar meteorites, the date of ejection from the moon, duration of the travel from moon to Earth, and impact time on Earth can be determined from their noble gas isotopic abundances. Noble gases in meteorites are usually organized into four broad categories: radiogenic, fissiogenic, cosmogenic, and trapped noble gases. The first three components result from in situ nuclear processes: radiogenic ^{4}He, ^{40}Ar and ^{129}Xe from the decay of U and Th, ^{40}K, and ^{129}I, respectively, Xe from ^{238}U and ^{244}Pu spontaneous fission, and cosmogenic noble gases from the interaction of cosmic rays with meteoritic material. These isotopes provide data on the mineral formation age, the duration of residence in a lunar surface layer of a few meters depth (effective penetration depth for cosmic rays), and the duration of the moon-Earth transfer for the lunar meteorites. The term "trapped" is used for components that were not produced in situ in extraterrestrial matter. In lunar surface material, most trapped noble gases originate from solar wind implantation. In addition, a variable fraction of the Ar, Kr, and Xe inventory in lunar samples was incorporated by implantation of lunar atmospheric volatiles: in the interior of the moon, most ^{40}K decayed to ^{40}Ar that was partly exhaled and retrapped by lunar surface material (*3*). The trapped gases provide information on the composition of the solar wind, on the length of time that the material resided on the lunar surface and was exposed to solar and lunar atmospheric species, and on the age of this exposure.

During the past several years, a large variety of investigations has been performed on lunar meteorites A81005, Y-791197, Y-82192, and Y-82193 (see references below). In this article, I describe results from noble gas mass spectrometry for the most recently distributed lunar meteorite, Y-86032 (*4–7*) and put them into perspective with those for the other lunar meteorites.

Evidence for Lunar Origin

All lunar meteorites are anorthositic regolith breccias that were formed by consolidation of former soil. The term "regolith" describes the layer of debris draped over the entire lunar bedrock surface. The lunar meteorites contain clasts of anorthite ($CaAl_2Si_2O_8$) and, in many respects, are similar to the regolith breccias returned from the highland regions of the moon by the Apollo missions (*1*). The presence of glass spherules and rare mare components, such as armalcolite [$(Fe, Mg)Ti_2O_5$] and ulvöspinel (Fe_2TiO_3), are clear evidence for an origin in the lunar regolith (*8*). Although their matrix is densely compacted, small unfilled cavities, which may have formed when the regolith breccia was compacted, occur in a similar manner as in Apollo 16 breccias (*9*). Surprisingly, textures in minerals and clasts of the lunar meteorites suggest that the meteorites suffered only mild shock effects (<20 GPa) that are no greater than those observed for the Apollo highland rocks (*9*),

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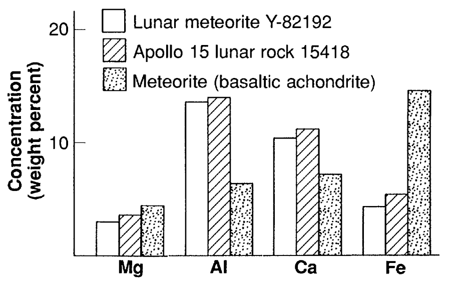

Fig. 1. Comparison of the concentrations of Mg, Al, Ca, and Fe in lunar meteorite Y-82192 (*13*) with those in lunar highland rock 15418 (*10*) from the Apollo 15 mission and in basaltic achondrites (eucrites) (*54*), the meteorites chemically resembling the lunar meteorites most closely. In view of analytical errors, the Al, Ca, and Fe concentrations in eucrites differ from those in the lunar meteorites and in Apollo highland samples. Lunar meteorites and Apollo highland rocks are chemically similar.

which were carried to Earth rather than being ejected from the moon by an impact event.

Additional evidence of the lunar origin is provided by the pattern of the major and minor elements and the isotopic ratios, compared with those for Apollo highland rocks and the achondrites, the type of meteorites that are chemically closest to the lunar meteorites. The elemental pattern for the major elements Mg, Al, Ca, and Fe (Fig. 1) of lunar meteorites is essentially the same as that for the Apollo highland samples but differs significantly from that of the achondrites (*9–14*). Good agreement between lunar meteorites and Apollo and Luna highland soils is also observed for Na, Sc, V, Cr, Mn, Co, Ni, Ga, and Br. The only exceptions are the concentrations of P, K, Ti, Ba, Th, U, and the rare earth elements, which are enriched by a factor of 2 to 6 in the Apollo and Luna highland soils relative to those in the lunar meteorites. The reason for this enrichment is discussed below.

All samples from bodies in the solar system that have undergone extensive differentiation, such as Earth and the moon, have O isotopic compositions that lie along a mass-dependent fractionation line in a $^{17}O/^{16}O$ versus $^{18}O/^{16}O$ diagram. The O isotopic ratios of the lunar meteorites and of the Apollo 16 breccias plot on the same fractionation line, which clearly differs from that of other meteorite classes (*15*). Also the Si isotopic composition is indistinguishable from that of lunar highland rocks (*15*).

Perhaps the most diagnostic evidence for a lunar origin is the isotopic composition of the trapped noble gases. The trapped $^{20}Ne/^{22}Ne$ ratio in lunar meteorites of 12 to 13 agrees with that observed in lunar rocks and soils (Fig. 2A). Because of the trapping characteristics of lunar material for solar wind Ne, the $^{20}Ne/^{22}Ne$ ratio is somewhat lower than the value of 13.7 in the solar wind (*16*). The trapped Ne isotopic composition of nonlunar meteorites is variable, if they contain trapped Ne at all; unseparated meteorite samples show trapped $^{20}Ne/^{22}Ne$ ratios between 8 and 14 (*17*).

The trapped $^{40}Ar/^{36}Ar$ ratio (Fig. 2B) and the concentrations of trapped ^{36}Ar (Fig. 2C) of the lunar meteorites are consistent with the large range observed for the Apollo 16 regolith breccias. A trapped $^{40}Ar/^{36}Ar$ ratio of 0.3 to 12 (*18*) is characteristic of lunar surface material. Trapped ^{40}Ar in lunar regolith material originates from outgassing of the lunar crust and subsequent reimplantation after acceleration by the solar wind field (*3*). Thus, the presence of trapped ^{40}Ar in substantial proportions indicates exposure of the material on a body of sufficient gravity to hold at least a weak atmosphere. On small objects, such as asteroids, however, ^{40}Ar is immediately lost after outgassing. The $^{40}Ar/^{36}Ar$ ratio in the trapped Ar of most nonlunar meteorites is difficult to derive because of the dominating in situ production of radiogenic ^{40}Ar from ^{40}K. So far, the trapped $^{40}Ar/^{36}Ar$ ratio has only been measured in meteorites of the ureilite class, which contain high amounts of trapped Ar; the ratio in these meteorites is $2.9 \pm 1.7 \times 10^{-4}$ (*19*).

The isotopic composition of trapped Ar places the evidence for a lunar origin of the meteorites beyond doubt. The only conceivable remaining alternatives, the planets Mars and Mercury, can be ruled out on the basis of chemical composition (*20*) and dynamical aspects (*21*), respectively.

Lunar History

The crystallization and gas retention ages of the lunar meteorites illustrate that the lunar highland crust is old, dating back almost to the origin of the solar system about 4600 million years ago (Ma). Each of the radiometric dating systems in Table 1 provides different information on the evolution of the lunar crust. Comparison of the ages of lunar highland rocks returned by the Apollo missions with the respective ages of the lunar meteorites yields remarkable agreement. The U-Th-Pb and Sm-Nd ages of Apollo highland rocks indicate that a differentiation of the crust and mantle occurred about 4500 to 4300 Ma (*22, 23*), whereas the Rb-Sr internal isochrons and the K-Ar and ^{39}Ar-^{40}Ar ages of many highland samples from widely separated areas bear the imprint of events in a narrow time interval that can be identified with a cataclastic impacting rate on the moon about 3900 Ma (*22*). This time scale (4500 to 3900 Ma) of lunar crust formation, as deduced from the Apollo rocks, is clearly

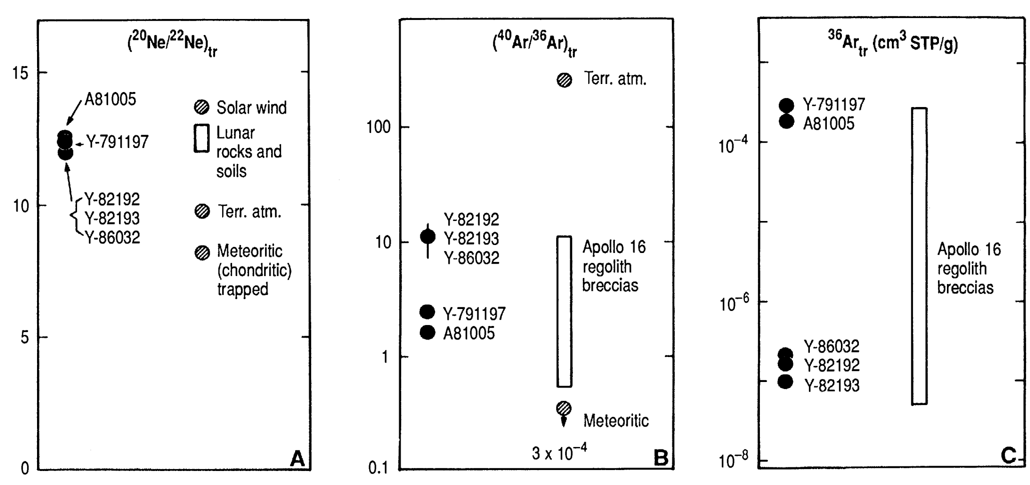

Fig. 2. (**A**) Isotopic ratios of Ne in solar system reservoirs. Trapped (tr) Ne in lunar meteorites (*6, 9, 26–28, 35*) and lunar rocks and soils (*18*) originates from solar wind implantation and is isotopically similar. Because of fractionation, this trapped Ne differs slightly from solar wind Ne (*16*). The $^{20}Ne/^{22}Ne$ ratio in the terrestrial atmosphere (Terr. atm.) and in chondrites (*17*) is lower. (**B**) $^{40}Ar/^{36}Ar$ ratio of Ar from external sources in lunar meteorites and in other solar system reservoirs. In lunar material ^{40}Ar is the decay product of ^{40}K and originates from outgassing of the lunar crust. It was reimplanted with ^{36}Ar from the solar wind. The trapped $^{40}Ar/^{36}Ar$ ratio of the lunar meteorites is in the range observed for the Apollo samples (*18*) and differs from that in other meteorite classes (*19*). (**C**) Concentration of ^{36}Ar from solar wind implantation in lunar meteorites compared to that in Apollo lunar samples. The amount of trapped ^{36}Ar is a measure of the duration of the residence of the material in the top surface layer of the lunar crust.

Table 1. Crystallization age, gas retention age, duration of lunar regolith residence t_{moon}, duration of moon-Earth transfer $t_{transfer}$, and terrestrial age t_{terr} of meteorites originating from the moon.

Meteorite	Crystallization age (Ma)			Gas retention age (Ma)		t_{moon} (10^6 years)	$t_{transfer}$ (10^6 years)	t_{terr} (years)
	Sm-Nd	Rb-Sr	U-Th-Pb	K-Ar	^{39}Ar-^{40}Ar			
Y-86032				3,870 ± 300		<11	10.6 +0.6/−5.6	72,000 ± 30,000
Y-82192	4,300 (*49*)	3,900 ± 500 (*50*)	4,549 ± 60 (*51*)	3,900 ± 200 (*6*)	4,240 ± 340 (*53*)	<11	10.6 +0.6/−5.6	83,000 ± 35,000 (*6*)
Y-82193				>3,000 (*6*)		<11	10.8 +0.7/−5.8 <9.7 (*9*)	75,000 ± 30,000 (*6*)
Y-791197	4,300 (*49*)	3,950 ± 240 (*49*)	4,250 (*50*)		4,070 ± 180 (*25*)	450 (*29*) 910 (*26*)	<0.3 (*34*)	<100,000 (*38*)
A81005			4,500 (*51*) 3,900 (*51*) 4,600 (*52*)	4,300 ± 900 (*28*)		580 (*28*)	<0.1 (*34*)	170,000 ± 50,000 (*38*)

reflected by the crystallization and gas retention ages of the lunar meteorites (Table 1).

The trapped and cosmogenic noble gases yield further information on the history of the lunar meteorites. As mentioned above, ^{40}Ar produced by the decay of ^{40}K in the lunar crust was exhaled and mixed with ^{36}Ar from the solar wind. These species were implanted into a surface layer of about 0.1 μm of the regolith grains. Because the abundance of ^{40}K decreases with time (half-life ≈1280 million years), the $^{40}Ar/^{36}Ar$ ratio on the grain surfaces is a measure of the implantation time of solar wind and lunar atmospheric volatiles and thus of the breccia formation age. On the basis of the evolution of the trapped $^{40}Ar/^{36}Ar$ ratio with time (*24*), and a $^{40}Ar/^{36}Ar$ value of about 10 for Y-82192, Y-82193, and Y-86032 (Fig. 2B), these meteorites are thought to represent a breccia that formed at an early time in lunar history, 3000 to 4000 Ma. In contrast, lunar meteorites Y-791197 (*25, 26*) and A81005 (*27, 28*) yield lower trapped $^{40}Ar/^{36}Ar$ ratios; their breccia formation age may be around 1000 Ma.

Although Y-82192, Y-82193, and Y-86032 have an early breccia-formation age, they were exposed relatively briefly to solar-wind and cosmic-ray particles (*6, 9*), whereas Y-791197 and A81005, with a young breccia-formation age, had a long duration of exposure (*26–29*): the concentration of solar wind ^{36}Ar is several orders of magnitude greater in the two breccias that were formed later in lunar history (Fig. 2C), and they were also exposed to cosmic rays for a much longer period of time (Fig. 3A). The breccia material of Y-82192, Y-82193, and Y-86032 apparently resided for only a brief period in the nuclear active zone (the upper few meters of the lunar regolith). The rock material must have been shielded from cosmic rays and the solar wind during most of its lunar history.

Duration of Moon-Earth Transfer

As a result of high-energy asteroid or comet impacts on the moon, a tiny fraction of the lunar material leaves the surface with velocities great enough to allow it to escape the moon's gravitational field. A fraction of such material should eventually reach Earth's surface. Monte Carlo calculations show that the duration of moon-Earth transfer of meteorites can be up to 100 million years, but typically should be less than 1 million years (*30*). During the transfer (and on the moon if material is in the nuclear-active zone) cosmic-ray particles induce nuclear reactions in the meteorite. The mean interaction depth for cosmic rays and the secondary particles they engender is about 1 m. Radioactive and stable nuclides are produced, in particular ^{10}Be, ^{26}Al, ^{36}Cl, ^{53}Mn, and noble gases, and serve as a means for deriving the intensity of the cosmic-ray flux and the duration of exposure in space.

The equilibrium activities of ^{10}Be (half-life 1.5×10^6 years), ^{26}Al (7.05×10^5 years), ^{36}Cl (3.0×10^5 years), and ^{53}Mn (3.7×10^6 years) in meteoritic material in free space, where all surfaces are exposed (4π exposure), are about twice those of lunar rocks, which are exposed on the lunar surface to cosmic rays only from half-space (2π exposure) (*31, 32*). The activities of these radionuclides in Y-82192 and Y-82193 are consistent with typical meteoritic values for 4π exposure, whereas A81005 and Y-791197 yield roughly half these values, that is, the activities observed for lunar rocks collected in the Apollo missions (*33, 34*). These data indicate that Y-82192 and Y-82193 were exposed for at least a few half-lives of the longest lived radionuclides, ^{10}Be and ^{53}Mn, in free space. Therefore, a lower limit of the duration of moon-Earth transfer $t_{transfer}$ for these two meteorites is about 5 million years (Fig. 3B). On the other hand, the radionuclide activities of A81005 and Y-791197 are consistent with a 2π exposure and indicate that the duration of moon-Earth transfer for these meteorites must have been brief relative to the half-life of the shortest lived radionuclide, ^{36}Cl, and probably less than 10^5 years for A81005 and less than 3×10^5 years for Y-791197 (*34*). Most of their exposure to cosmic rays occurred on the lunar surface at 2π-exposure geometry.

The concentrations of stable noble gas isotopes produced by

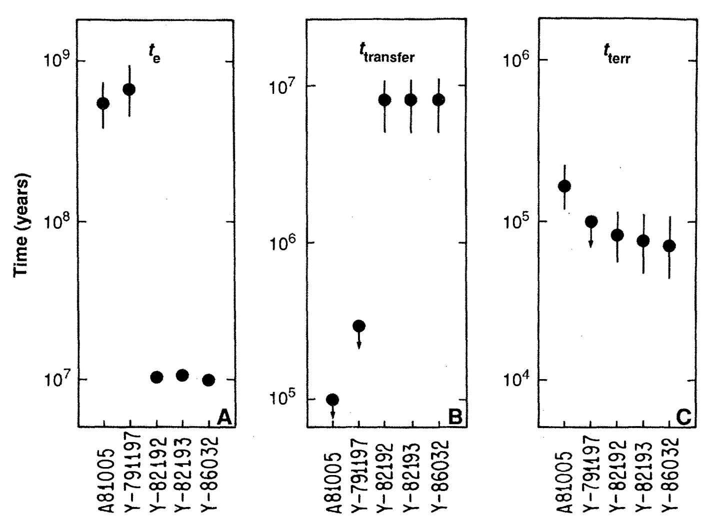

Fig. 3. (**A**) Total duration of exposure to cosmic rays t_e, as obtained from noble gas isotopes in the lunar meteorites. (**B**) Duration of moon-Earth transfer $t_{transfer}$. (**C**) Terrestrial age t_{terr}, the duration the lunar meteorites lay on Earth after their fall on the Antarctic ice, as obtained from ^{81}Kr and ^{36}Cl dating. For references, see Table 1.

cosmic rays allow the determination of upper limits of the total duration of exposure t_e (Fig. 3A). To determine t_e for Y-86032, the concentrations of cosmogenic ^{21}Ne, ^{38}Ar, ^{83}Kr, and ^{126}Xe were divided by the respective production rate for 4π exposure (*6*). I show below that this assumption of a 4π, rather than 2π exposure, is justified. The ^{21}Ne concentration is $2.24 \pm 0.10 \times 10^{-8}$ cm^3 STP/g (STP, standard pressure and temperature). This value yields a t_e of 10.6 ± 1.4 million years. Similar t_e values are obtained for the other isotopes: $2.35 \pm 0.20 \times 10^{-8}$ cm^3 STP/g ^{38}Ar, 12.0 ± 1.8 million years; $12.8 \pm 2.5 \times 10^{-12}$ cm^3 STP/g ^{83}Kr, 10.0 ± 2.5 million years; and $0.47 \pm 0.1 \times 10^{-12}$ cm^3 STP/g ^{126}Xe, 9.9 ± 2.5 million years. From these four independent methods, the average t_e is 10.6 ± 0.6 million years. Essentially the same exposure ages were obtained for Y-82192 [10.6 million years (*6*), 9.7 to 12.2 million years (*9*), and 7.7 to 9.9 million years (*35*)] and for Y-82193 [10.8 million years (*6*)]. Thus, the upper limit of the duration of moon-Earth transfer for Y-82192, Y-82193, and Y-86032 is about 11 million years (Table 1 and Fig. 3B).

A different scenario is implied for A81005 and Y-791197. The concentrations of the cosmogenic noble gases are about 20 times as high as those in the other lunar meteorites. The moon-Earth transfer (Table 1) was <100,000 years for A81005 and <300,000 years for Y-791197 (*34, 36*). These results are consistent with the thermoluminescence data yielding moon-Earth transfer times of <2500 years for A81005 and <19,000 years for Y-791197 (*37*). Because the duration of moon-Earth transfer was brief, most of the exposure of A81005 and Y-791197 must have occurred on the moon. The t_e of several hundred million years calculated with production rates for 2π exposure (Fig. 3A) are, therefore, identical to the duration of lunar regolith residence (Table 1).

Terrestrial Age

The terrestrial age, t_{terr}, that is the duration a meteorite lay on Earth after its fall, is derived on the basis of the present activity of a cosmic ray–produced radioactive nuclide and its activity at the time of fall. The activity at the time of fall is equal to the production rate

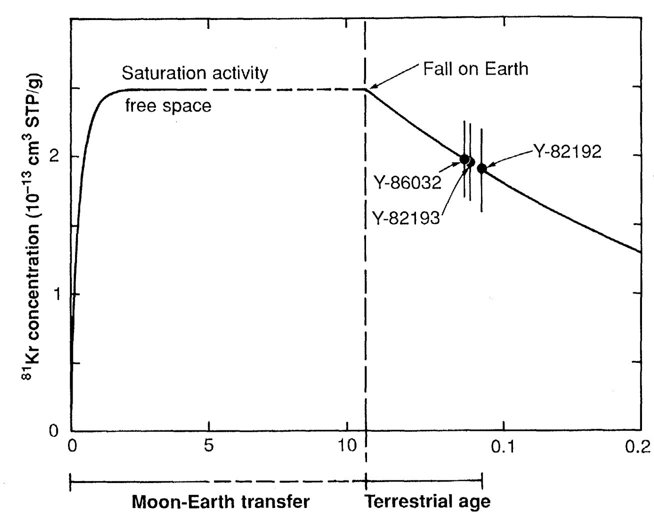

Fig. 4. Calculation of the terrestrial age of lunar meteorites Y-82192, Y-82193, and Y-86032 based on the measured ^{81}Kr concentrations and the saturation activity, $\tau^{81} \cdot P^{81}$, of ^{81}Kr in free space (2.5×10^{-13} cm^3 STP/g). The production rate of ^{81}Kr, P^{81}, is $P^{81} = 0.475(^{80}\mathrm{Kr} + {}^{82}\mathrm{Kr})/t_e$ (*5, 6*), where ^{80}Kr and ^{82}Kr are the concentrations of the cosmic ray–produced component. The broken lines indicate that the duration of the moon-Earth transfer is greater than 5 but less than 11 million years.

P^i, if the duration of cosmic-ray exposure is sufficiently long compared to the mean life τ^i of the radioisotope *i*. A well-suited radionuclide is ^{81}Kr because its mean life τ^{81} is in the range of the terrestrial ages of Antarctic meteorites. The terrestrial age is then given by (*6*) $t_{terr} = \tau^{81}\ln(\tau^{81}P^{81}/^{81}\mathrm{Kr})$.

Because the lower limit of 4π exposure for Y-82192 and Y-82193 is 5 million years, the ^{81}Kr activity is in equilibrium (Fig. 4). The terrestrial ages for these meteorites are $83,000 \pm 35,000$ years for Y-82192 and $75,000 \pm 30,000$ years for Y-82193 (*6*). Within the errors, a similar terrestrial age of $72,000 \pm 30,000$ years is calculated for Y-86032 (Fig. 4 and Table 1). The error is large because only about 3×10^{-14} cm^3 ^{81}Kr (STP) was available for each analysis.

The terrestrial ages of A81005 and Y-791197 are $170,000 \pm 50,000$ years and <100,000 years, respectively (Fig. 3C). These ages were derived based on the ^{36}Cl activity (*38*). The reason for the old terrestrial ages of the meteorites collected in Antarctica is that they are transported in the ice onto which they have fallen, until they reappear on the surface at sites where the ice is ablated (*39*).

Lunar Meteorites from Two or Three Impacts

The radiogenic ages, exposure ages, terrestrial ages, and trapped noble gases indicate that the history of Y-86032 is identical to that of Y-82192 and Y-82193. Several authors (*6, 9, 38, 40, 41*) have suggested that the latter two rocks were from the same meteorite that broke apart before or upon impact on Earth; they were collected from the same area (*41*). Y-86032 was found about 2 km from Y-82192 and Y-82193 (*42*). My data strongly indicate that Y-86032 also belongs to the Y-82192/3 fall.

The data for the total duration of exposure to cosmic rays from the stable noble gas isotopes, for the terrestrial age from ^{81}Kr, and for the ^{53}Mn activity allow development of models for the history of the Y-82192/3 and Y-86032 meteorite fragments (Fig. 5). Closest agreement of the observed ^{53}Mn activity is obtained for a $t_{transfer}$ identical to the total duration of exposure to cosmic rays t_e (10.7 million years), for 4π exposure (Fig. 5A). In this model, the total exposure to cosmic rays occurred in free space and none on the lunar surface, that is, the Y-82192/3 and Y-86032 material was ejected from the moon by the same impact that excavated the rocks from a depth where they were shielded from cosmic rays. In the model shown in Fig. 5B, the moon-Earth transfer lasted 5 million years and the material was exposed in the lunar regolith for about 11 million years (*43*). This model requires two impacts on the moon within 11 million years: the first one to excavate the rock material from a depth where it was completely shielded from cosmic rays, and the second impact to propel it into space. Any model with $t_{transfer}$ of <5 million years is inconsistent with the ^{53}Mn data. In a third model (Fig. 5C), the exposure on the moon occurred early in the lunar history, so that ^{53}Mn decayed after the material was again buried under a thick layer below the lunar surface, which shields it from cosmic rays. In this model, $t_{transfer}$ must have been at least 7 million years in order to allow the ^{53}Mn activity to build up to the observed value. In conclusion, $t_{transfer}$ for the Y-82192/3 and Y-86032 rock material was 5 to 11 million years, the most probable value being 10.7 million years.

The two other lunar meteorites, A81005 and Y-791197, experienced a different history from that of Y-82192/3 and Y-86032. These rocks were exposed to cosmic rays on the lunar surface for several hundred million years and had $t_{transfer}$ of less than 100,000 years and 300,000 years, respectively (Table 1 and Fig. 3B).

The radionuclide activities (*34*) and the petrologically important Fe/Mg ratio (*44*) of A81005 and Y-791197 are not identical. The higher radionuclide activities of Y-791197 compared to those in A81005 may be explained by an exposure to cosmic rays at a shallower shielding depth. The difference in the Fe/Mg ratio of about 30% has been used to argue against an origin from the same target area on the moon (*44*). However, about the same variation has been observed for Apollo highland rocks ejected from a single lunar crater (*45*). The difference of the terrestrial ages for the two meteorites (Table 1) does not exclude an origin from the same impact event because the sum of t_{transfer} and t_{terr} may still be the same. Thus, the data do not solve the question whether A81005 and Y-791197 originate from one or two separate impact events on the moon less than about 400,000 years ago. In conclusion, two or three impacts were responsible for propelling the lunar rocks toward Earth.

Are two or three impacts that are capable to propel rock fragments outside the lunar gravitational fields within about 11 million years compatible with the impact frequency on the moon?

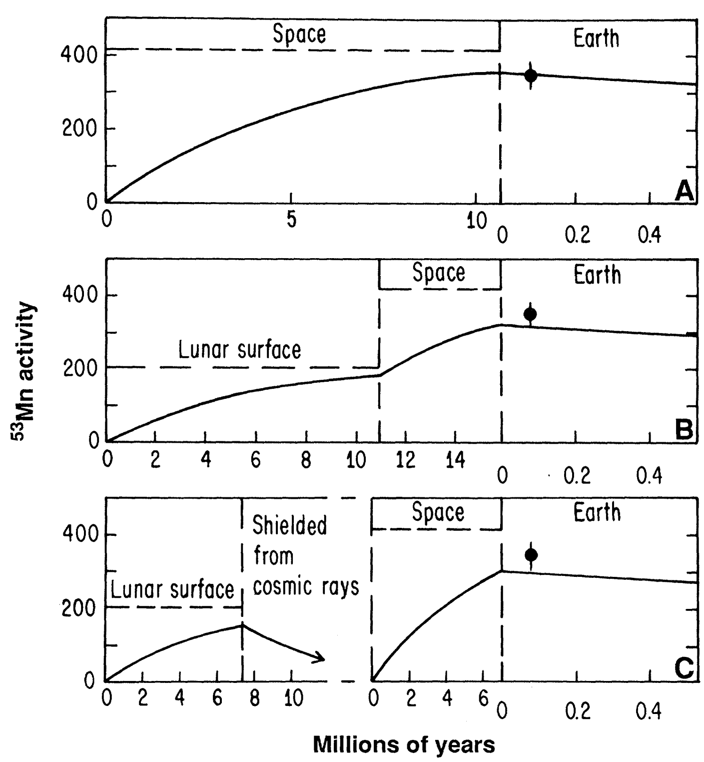

Fig. 5. Models showing the buildup of the ^{53}Mn activity (decays per minute per kilogram of iron) in free space and on the lunar surface, due to the interaction of cosmic rays with the meteoritic material, and its decay after the fall on Earth. The broken horizontal lines indicate the saturation activities in free space [414 dpm per kilogram Fe (*55*)] and on the lunar surface (half the above value). (**A**) The average ^{53}Mn activity observed for lunar meteorites Y-82192 and Y-82193 (*34*) is in good agreement with the exposure model calculated based on noble gas isotopes: exposure to cosmic rays in free space and, after fall on Earth (broken vertical line), residence for about 80,000 years on the Antarctic ice. (**B**) In this model, the Y-82192/3 material was brought to the lunar surface by an impact event and resided on the lunar surface for about 11 million years. Then a second impact (left broken vertical line) propelled it into space. At least 5 million years of exposure to cosmic rays in free space are required to build up the ^{53}Mn activity to the observed value. The right broken vertical line designates the fall on Earth. (**C**) In this model, the exposure to cosmic rays on the moon occurred early in lunar history and was terminated by a complete shielding from cosmic rays (left broken vertical line). An impact ejected the Y-82192/3 material into space (middle broken vertical line). The moon-Earth transfer must have lasted at least 7 million years to build up the ^{53}Mn activity until fall on Earth (right broken vertical line). The simplest model (A) is the most probable one because one impact only is required for excavating the Y-82192/3 material and propelling it into space.

The diameter of the object hitting the moon must be more than about 100 m for ejection of lunar meteorites (*46*); such an impact would form a crater >3000 m in diameter. The number of such craters produced on the moon is about three per million years (*47*). In that not all recent impacts on the moon have likely been sampled by the recovered lunar meteorites, one or two impacts 400,000 years ago and one impact 5 to 11 Ma are reasonable observations.

In that an area corresponding to only 5% of the lunar surface was sampled in the Apollo and Luna missions, the availability of material from other sites is important for a comprehensive interpretation of the composition and petrology of the lunar crust. Although the chemical composition of the lunar meteorites is similar to that of the Apollo highland rocks, there are some small but significant differences: The concentrations of K, the rare earth elements, P, Ba, Th, and U are higher in the Apollo and Luna regolith samples compared to those in the lunar meteorites. The KREEP (K, rare earth elements, P) component is typically admixed to the soil on the front side of the moon, and the elements Ba, Th, and U are always associated with KREEP. Titanium is also enriched in Apollo and Luna samples. This element is present in ilmenite, a mineral that is relatively abundant in mare basalt material. The lunar meteorites must, therefore, come from an area far from the KREEP reservoir that is located on the front side and far from the mare regions, perhaps even from the lunar backside (*11, 29, 48*). The lunar meteorites, thus, augment the sample coverage for the lunar surface. In particular, the low K, Th, and U contents of the lunar meteorites imply that any model for the bulk moon has to take into account lower abundances of these geochemically important elements than currently adopted based on the Apollo and Luna samples alone.

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4. Sample split Y-86032, 86 (0.42 g) obtained from the National Institute of Polar Research in Tokyo was crushed in a stainless steel mortar to grain size <700 μm. Two samples of about 1 mg and one sample of 20 mg were consumed for He, Ne, and Ar isotope analyses and a sample of 41 mg was used for the determination of chemical abundances. About 240 mg of the crushed material was separated by sedimentation in acetone into grain size fractions of <30 and >30 μm. For each grain size fraction, duplicate analyses of all five noble gas elements were carried out as described in (*5, 6*). Decomposition of the noble gases into the different components was performed as described in (*6*). Throughout the paper, the reported uncertainties for the noble gas spectrometry data are 95% confidence intervals based on analytical measurement error. Some analyses also are in (*5, 7*).
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43. For the production of the stable noble gas isotopes, an exposure during 10.7 million years in free space (4π exposure to cosmic rays) in equivalent to an exposure during 11.4 million years in the first stage (lunar regolith, 2π exposure) and during 5 million years in the late stage (free space). In this model, I assume that exposure to cosmic rays occurred in both stages at the same shielding depth. This appears to be the case as indicated by the depth-sensitive cosmogenic $^{131}Xe/^{126}Xe$ ratio. The ^{131}Xe production increases with depth relative to that of ^{126}Xe because of the reaction of ^{130}Ba with secondary cosmic ray–produced neutrons. In Y-82192 and Y-82193, $^{131}Xe/^{126}Xe$ ratios of 3.4 and 2.7, respectively, were measured (*26*), and Y-86032 yielded a value of 2.6. These ratios correspond to a shielding depth of 15 cm or less in the meteorite or below the lunar surface.
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Experiments with High-Energy Neutrino Beams

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Experiments in which high-energy neutrinos were used as projectiles have made substantial contributions to our understanding of both weak and strong interactions, as well as the structure of hadrons. This article offers some illustrations. It recalls the discovery of the neutral weak current and some experiments on its nature. The sections on charged-current inclusive scattering recall the important role of these experiments in the understanding of the quark structure of the nucleon and the validity of quantum chromodynamics. The section on dimuon production illustrates the role of neutrino experiments in establishing the Glashow-Iliopoulos-Maiani current as well as the measurement of the structure function of the strange quark in the nucleon.

HIGH-ENERGY NEUTRINO BEAMS HAVE FOUND INTENSIVE and varied application in particle physics experimentation in the last decades. In this review I discuss a few of the most fruitful examples: the discovery of neutral currents, the measurement of the Weinberg angle, the study of weak currents and the consequent test of the electroweak theory, the study of nucleon quark structure, and the testing of quantum chromodynamics (QCD). Other studies, such as the production of "prompt" neutrinos, the search for finite neutrino masses and neutrino oscillations, the search for heavy leptons or other new particles, the measurement of proton and neutron structure functions, elastic and pseudoelastic cross sections, and other exclusive processes, are not discussed here. Neutrino experiments have been pursued vigorously at the Brookhaven National Laboratory (BNL), at Fermilab, and at CERN. It is fair to say that they have made large contributions to our understanding of particle physics.

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