EXCESS FISSION XENON AND I-Pu-Xe DATING: T. D. Swindle, M. W. Caffee and C. M. Hohenberg, McDonnell Center for the Space Sciences and Dept. of Physics, Washington University, St. Louis, MO 63130.

The existence of "excess fission xenon" has been known since soon after the Apollo 14 samples were returned [1, 2]. The history of how that xenon, which originated in the decay of ^{129}I and ^{244}Pu, was redistributed and became a surface-correlated component on all gas-rich breccias (and at least two other samples) has never been clear. The effect is of interest not only in and of itself, but also because of the potential for use of the ratio of ^{129}I-derived ^{129}Xe to ^{244}Pu-derived fission xenon as a chronometer [3, 4, 5].

The origin of excess fission xenon

In Table 1, we evaluate possible proposed models of the origin and history of excess fission xenon in light of experimental results. Under each proposed feature are columns for 1) data that argue in favor of that proposal, 2) data that could be considered supporting evidence for that proposal, 3) data that are consistent with that proposal which might not be consistent with other proposals, and 4) data that are difficult to reconcile with the proposal. Experimental evidence we consider includes the following:

1) Excess fission xenon is a) surface-correlated [6, 7], but b) much of it is released at temperatures of 1000^{0}C or more.

2) For breccias, the amount of fission xenon involved is greater than the amount expected from in situ fission since the compaction of the breccia (the "excess fission factor" is greater than one), but less than or equal to the amount a sample with the same actinide content would be expected to produce in the age of the solar system.

3) The concentrations of excess ^{136}Xe are similar for Apollo 14 and Apollo 16 breccias, even though Apollo 14 has nearly an order of magnitude more uranium [8].

4) The ^{129}Xe/^{136}Xe ratio in the surface-correlated component is higher when bulk samples are considered than when only low-temperature extractions are considered [5,7].

5) The highest initial ^{129}Xe/^{136}Xe ratio observed in a breccia (14301) implies an initial ^{129}I/^{244}Pu ratio comparable to that expected for the bulk Moon about 45 m.y. after the formation of meteorites [7], assuming the present Moon has a ^{127}I/^{238}U ratio of 0.01.

6) The ^{129}Xe/^{136}Xe ratio in the excess doesn't correlate with the ratio of excess fission to solar wind xenon, nor does the amount of excess fission correlate with the amount of solar wind or other indicators of regolith maturity [9].

7) Excess fission xenon is observed in all Apollo 14 and Apollo 16 breccias that are rich in solar wind gas, but is not observed in gas-poor breccias [8,9].

8) Excess fission xenon is observed in cumulate 76535 [10] and excess ^{129}Xe is observed in a troctolitic anorthosite clast from 67915 [11], both in low-temperature steps, both accompanied by little solar wind. The ratio of excess ^{129}Xe/^{136}Xe ratio in 67915,67 is about 3.5$\pm$1.5 times that of 14301.

9) Adsorption experiments by Podosek et al. [12] on a lunar soil sample indicated that adsorption seems to be quantitatively unable to account for the amount of excess fission xenon observed. They calculated a residence time for xenon in the lunar regolith of about 20 days. However, there is evidence that the noble gas trapping properties of surface sites may be considerably altered by exposure to the terrestrial atmosphere [13], or other environments including chemically active elements.

10) Surface-correlated ^{40}Ar is observed in lunar soils [14]. a) It is believed that this excess ^{40}Ar is from sources deep within the lunar interior [15]. b) Argon is apparently implanted in grains when atmospheric argon is ionized and then accelerated by the electromagnetic fields in the solar wind [14, 16]. c) The argon abundance in the lunar atmosphere increases dramatically at sunrise, indicating that argon temporarily freezes out in the regolith during the lunar night [15].

11) ^{222}Rn, a noble gas with a three-day half-life, is present in the lunar atmosphere [17], but there are two different proposals for the source, with different implications. a) Hodges [15] assumes radon comes from the same deep source as argon and calculates a transit time from the lunar interior of about 80 days. b) Gorenstein et al [18], noting spatial variations in radon abundance, assume that the radon is from local uranium decay.

12) A philosophical constraint on any hypothesis is Occam's Razor, which could be paraphrased as: the fewer the number of different special conditions required, the better.

Iodine-plutonium-xenon dating

Attempts at I-Pu-Xe dating [3, 5] have assumed that acquisition of excess fission xenon is an ongoing process, that the source of the excess is the lunar interior (i.e., that the appropriate present-day elemental I/U ratio is that of the Moon as a whole) and that transport is rapid. From the systematic variations in the $^{129}Xe/^{136}Xe$ ratio in the excess, it seems likely that acquisition of excess fission xenon was an ongoing process. The lack of correlation among the $^{129}Xe/^{136}Xe$ ratio, the amount of excess fission and the amount of solar wind might be due to the stochastic nature of the process, especially since shock is apparently involved in "fixing." Fast transport is also quite possible, although the evidence is inconclusive.

The bulk Moon elemental abundances are unlikely to be the appropriate ones for the source unless the xenon has been mixed in the lunar atmosphere. However, 76535 and 67915,67 apparently acquired their excess xenon without exposure to the lunar atmosphere. If the excesses are not acquired through the atmosphere, then the source for a given sample is probably the material directly beneath it (possibly far beneath it), and the mechanism for incorporation some type of surface affinity, followed by "fixing." For Apollo 14 breccias, the U content is 3-4 ppm [8], while the measured I contents of Apollo 14 samples are 2 to 200 ppb [19]. If these values are representative of the Moon at Apollo 14 and just below, then the appropriate I/U ratio is certainly within an order of magnitude of 0.01, so the age of 14301 is still accurate to within 70 m.y. Since the Apollo 14 site is richer in uranium than the Apollo 16 site, the higher $^{129}Xe/^{136}Xe$ ratio 67915,67 might correspond to a similar time. Thus consideration of a more localized source again indicates a time of incorporation of excess fission xenon beginning within 100 m.y. of primitive meteorites, but the uncertainties are about 70 m.y. This means that both the results and the uncertainties are similar to those of Rb-Sr and Pu-REE-Xe ages of the oldest lunar rocks [13, 20, 21].

References: (1) Crozaz et al. (1972). PLSC 3rd. 1623; (2) Drozd et al. (1972). EPSL 15. 338; (3) Behrmann et al. (1973) EPSL 17, 446; (4) Reynolds et al. (1974) GCA 38, 401; (5) Swindle et al (1984) PLPSC 15th. In press; (6) Basford et al. (1973). PLSC 4th. 1915; (7) Bernatowicz et al. (1979). PLPSC 10th. 1587; (8) Bernatowicz et al. (1978) PLPSC 9th. 1571; (9) Drozd et al. (1976). PLSC 7th. 599; (10) Hohenberg et al. (1980) P. Lunar Highlands Crust. 419; (11) Aeschlimann et al. (1983) LPSC XIV. 1; (12) Podosek et al. (1981) PLPSC 12B. 891; (13) Caffee et al. (1981) PLPSC 12B. 99; (14) Heymann and Yaniv (1970) P. A11 LSC. 1261; (15) Hodges (1975) Moon 14. 139; (16) Manka and Michel (1970). Science 169. 278; (17) Bjorkholm et al. (1973) PLSC 4th. 2793; (18) Gorenstein et al. (1973) PLSC 4th. 2803; (19) Reed et al. (1972) PLSC 3rd. 1989; (20) Papanastassiou and Wasserburg (1975) PLSC 6th. 1467; (21) Papanastassiou and Wasserburg (1976) PLSC 7th. 2035.

Table 1. Origin of excess fission xenon

Feature	Arguments For	Supporting Evidence	Consistent With	Arguments Against	Conclusion
Continuous process	4	5	7	8,6(?)	Possible
Source:					
A. Bulk Moon (deep interior)	3,10a	5,7,11a, 12(+10a,11a)	1,2,4	8b,6	Possible
B. Localized (few km region)	8	11b	1,2,4,5,6	3,10,9	Possible
C. Localized (few cm)	8	2	6	3,7	Unlikely for breccias
D. In situ fission			6	1,2,3,4	Not likely
E. Exterior to Moon	6		7,5	2,4,8	Not likely
Fast transport	9b,11a				Possible
Implantation:					
A. Electromagnetic implantation	9	3,7,10b	11,1	6,8	Possible
B. Adsorption (from atmosphere)	10c		3,11,1,7	6,9,8	Maybe
C. Adsorption (from regolith)	6,8	10c	1	9,3,7	Possible
D. (A) for breccia, (C) for others	8,9	3,7	1,5	6,12	Possible
Additional fixing	1		4,6(?)		Likely