COSMOGENIC KR AND XE MADE IN THE MOON FROM BR AND I;*

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Although generally rare in nature, the noble-gas elements krypton and xenon have many sources. Unraveling these sources and their isotopic compositions has been a goal of many research groups for decades. There are many types of sources, including primordial ones, radiogenic decay, solar emissions, and production in-situ by nuclear reactions induced by various energetic particles. The cosmogenic components are important in studies of the cosmic-ray exposure histories [e.g., 1,2] and in making corrections to measured compositions to get the other components. Pepin *et al.* [3] recently used Xe and Kr in regolith soils to study the solar-wind component. Most data could be explained by known sources. However, there was a variable and often large excess of ^{126}Xe of unknown origin in many samples [3]. We did calculations to see if this excess ^{126}Xe could have been made by solar-proton reactions with iodine on grain surfaces.

Two types of cosmic rays are important in surface samples, galactic and solar [4]. Because of their low energies, most solar cosmic rays (SCR), which are almost entirely protons, are stopped by ionization energy losses in the outermost few g/cm^2. The galactic cosmic rays (GCR) have much higher energies and penetrate very deep inside the irradiated body. GCR particles produce many secondary particles that contribute to nuclide production by spallation, such as $(n,2n)$, reactions and (n,γ) reactions. Previous calculations for the production of cosmogenic Xe [1,5] did not consider iodine as a target. The calculations by [2] of cosmogenic Kr isotopes did not consider Br as a target. Rates for making Kr isotopes of mass 78, 80, and 81 by solar protons reacting with Br were reported by [5]. Rates for making ^{80}Kr and ^{82}Kr by neutron-capture reactions with ^{79}Br and ^{81}Br were reported by [6].

We did three sets of calculations to study production of Xe isotopes from iodine (^{127}I): (1) spallation reactions induced by GCR secondary energetic neutrons, (2) neutron-capture reactions, and (3) reactions induced by solar protons. Neutrons make almost all GCR-produced Xe from I. Very little ^{124}Xe is made because ^{124}I doesn't decay to ^{124}Xe. The only GCR reactions making Xe isotopes are $^{127}\mathrm{I}(n,\gamma)^{128}\mathrm{I}$ (93% decay to ^{128}Xe) and $^{127}\mathrm{I}(n,2n)^{126}\mathrm{I}$ (44% to ^{126}Xe). Solar-proton-induced reactions with ^{127}I can make ^{126}Xe directly by the $(p,2n)$ reaction and by 44% of the decay of ^{126}I made by the (p,pn) reaction and also make some ^{124}Xe by the $^{127}\mathrm{I}(p,4n)^{124}\mathrm{Xe}$ reaction.

For production of ^{126}I by the $^{127}\mathrm{I}(n,2n)$ reaction, we used the lunar GCR model of Reedy and Arnold [4] and measured or estimated cross sections. Below about 18 MeV, we used measurements in a cross-section compilation [7], which had a threshold at 9 MeV and a peak cross section of 1.6 barns at 14–15 MeV. Cross sections above 18 MeV were estimated using systematics in [8]. The calculated production rates (in atoms/min/kg-I) of ^{126}Xe by GCR neutrons increase from 74 at the surface, 151 at 20 g/cm^2, to 191 at a depth of 50 g/cm^2.

The production of ^{128}Xe by the $^{127}\mathrm{I}(n,\gamma)^{128}\mathrm{I}$ reaction was calculated with the LAHET Code System (LCS). LCS and its adaptation to meteorite applications are described in [9]. For (n,γ) reactions, we used the library of cross sections in the MCNP part of LCS [10]. Production rates calculated for several neutron-capture reactions in the Moon using LCS have agreed well with measurements [11]. For this study, we used the composition of the Apollo 15 deep drill core and considered (n,γ) reactions with ^{127}I, ^{79}Br, and ^{81}Br. The calculated rates for these reactions are in Table 1, with decay factors included for ^{128}I to ^{128}Xe (93%) and ^{80}Br to ^{80}Kr (91.7%).

Table 1. Neutron-capture production rates from Br and I for Kr and Xe isotopes. Rates are atoms per minute per gram of element and include decay branching ratios. Depths (0–450) are in g/cm^2.

Target	Product	0	30	60	90	120	150	180	210	270	360	450
^{79}Br	^{80}Kr	26	99	153	187	205	204	193	176	134	84	50
^{81}Br	^{82}Kr	11	40	62	76	81	80	76	66	53	32	18
^{127}I	^{128}Xe	18	68	107	131	142	142	135	124	94	59	35

The calculated rates for the Br(n,γ) reactions had the same depth profiles as those of [6] but our rates are ~50% higher. Almost all of these (n,γ) reactions are by epithermal neutrons reacting with resonances having energies of ~30–10^4 eV, and their rates are not sensitive to the surface's composition [6]. The reason that our Br(n,γ) rates are higher than those in [6] is not known but could be because we considered all resonances while [6] only considered the largest ones. The ^{128}Xe/^{126}Xe GCR-production ratios from iodine are 243 (surface) and 502 (50 g/cm^2). Thus, as noted by [3], this ^{128}Xe/^{126}Xe GCR-production ratio is huge and shows that GCR reactions with iodine is not the source of excess ^{126}Xe because there is very little excess ^{128}Xe.

Cross sections for proton reactions with ^{127}I producing ^{126}I were from [12], and those for ^{126}Xe and ^{124}Xe were estimated from other data in [12]. Reaction thresholds and the peak cross section and the energy of this peak used here were 9 MeV and 1500 mb at 20 MeV for ^{126}I, 10 MeV and 200 mb at 27–45 MeV for ^{126}Xe, and 28 MeV and 600 mb at 45 MeV for ^{124}Xe. Proton fluxes at the Moon were calculated with Reedy-Arnold model [4] for protons with exponential-rigidity spectra shapes with R_o of 50–100 MV and an omnidirectional flux >10 MeV of 100 protons/cm^2/s. The actual spectral shape and fluxes of solar protons over various time periods in the past are not known. The average over the last 2×10^6 years is about 53-73 p/cm^2/s/4π with R_o of 80–90 MV [13]. Lower values of R_o with higher fluxes have also been proposed for the last 2 Ma, such as an R_o of 75 MV and a flux of 100 p/cm^2/s/4π [14]. Even lower values of R_o are possible, and they would have higher fluxes. The flux normalization (>10 MeV) of 100 p/cm^2/s/4π used here is somewhat arbitrary but is good enough to test the hypothesis of solar-proton production of ^{126}Xe. The calculated production rates at several depths or depth intervals for three values of R_o are in Table 2, which are the rates used by [3] in their study of possible sources of the excess ^{126}Xe.

Table 2. Production rates of xenon isotopes by solar-proton reactions with ^{127}I. Rates are atoms/min/kg-element. Depths (0.0–20.) are in g/cm^2. Flux(4π, >10 MeV) = 100 p/cm^2/s.

R_o	Nuclide	0.0	0.1	0.5	1.0	2.0	5.0	10.	20.	0–1	0–5	0–10
50 MV	^{124}Xe	471	337	164	88	36	6	1	–	192	59	31
50 MV	^{126}I→Xe	347	206	78	37	14	2	–	–	103	28	15
50 MV	^{126}Xe	7478	3337	821	299	81	9	1	–	1381	325	164
70 MV	^{124}Xe	850	652	366	224	110	28	6	1	409	147	80
70 MV	^{126}I→Xe	475	321	154	88	41	10	3	–	183	61	33
70 MV	^{126}Xe	7276	3726	1181	522	184	32	6	1	1712	452	233
90 MV	^{124}Xe	1130	901	549	362	198	62	19	4	600	240	137
90 MV	^{126}I→Xe	559	406	221	140	75	24	8	2	251	96	55
90 MV	^{126}Xe	6781	3755	1373	678	277	62	15	3	1850	536	284

Solar-proton reactions with iodine make much ^{126}Xe but also make some ^{124}Xe. The calculated Xe-126/124 ratios range from 7.7 for 0–1 g/cm^2 and 50 MV to 2.5 for 0–10 g/cm^2 and 90 MV. If the reaction of solar protons with iodine is the source of excess ^{126}Xe in regoliths, then the incident spectrum of solar protons must have been relatively soft (low values of R_o with few high-energy protons) and the iodine mainly near the surface, or else there should be an excess of ^{124}Xe.

Excess ^{126}Xe has been proposed as being made by solar protons reacting with tellurium [15]. The Q-values for the (p,n) reactions with ^{126}Te, ^{128}Te, and ^{130}Te go from about 1 to 3 MeV, so their reaction thresholds should be controlled by the coulomb barrier (~5 MeV) and be similar. Assuming similar cross sections, the yields of Xe isotopes should be controlled by the I isotopes' branching ratios and Te isotopic abundances, which suggest that ^{128}Xe and ^{130}Xe are made ~4 times as much as ^{126}Xe. However, good proton cross sections for making Xe from Te are needed.

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