

PRODUCTION RATES OF NEON AND XENON ISOTOPES BY ENERGETIC NEUTRONS; D. A. Leich, R. J. Borg, and V. B. Lanier, Lawrence Livermore National Laboratory, Livermore, CA 94550

As a first step in a new experimental program to study the behavior of noble gases produced *in situ* in minerals, we have irradiated a suite of minerals and pure chemicals with 14.5 MeV neutrons at LLNL's Rotating Target Neutron Source (RTNS-II) and determined production rates for noble gases. While neutron effects in meteorites and lunar samples are dominated by low-energy (<1 keV) neutron capture, more energetic cosmic-ray secondary neutrons can provide significant depth-dependent contributions to production of cosmogenic nuclides through endothermic reactions such as (n,2n), (n,np), (n,d) and (n, $\alpha$ ). Production rates for nuclides produced by cosmic-ray secondary neutrons are therefore useful in interpreting shielding histories from the relative abundances of cosmogenic nuclides.

Samples were vacuum encapsulated in quartz ampoules and irradiated as add-ons to the principle RTNS-II experiments for two to four weeks, during which time they accumulated fluences up to  $10^{17}$  neutrons/cm<sup>2</sup> as determined by activation of iron dosimetry foils. Irradiated samples were stored for at least three months before breaking open the quartz ampoules and weighing portions for analysis. Noble gas isotope dilution analyses were performed by adding an aliquot of our mixed noble gas spike or of an air standard during a single 1650 C vacuum extraction. Duplicate samples were analyzed without the spike in two-step extractions: a 400 C heating to reveal any tendency for low-temperature gas loss, and a 1650 C extraction. Only insignificant quantities of noble gas reaction products were released in the 400 C steps, leading us to conclude that gas retention was probably quantitative, although we cannot rule out the possibility of some diffusive loss at ambient temperatures during and after the irradiations. Cross sections reported in Tables 1-4 were calculated from the noble gas yields assuming chemical purity, stoichiometry, and quantitative noble gas retention and extraction.

Neon analyses were performed on samples of sodium and magnesium minerals and reagents. The neon extracted from sodalite (Na<sub>4</sub>(AlSiO<sub>4</sub>)<sub>3</sub>Cl), albite (NaAlSi<sub>3</sub>O<sub>8</sub>), and NaCl samples gave the same isotopic pattern, yielding cross sections given in Table 1. The (n, $\alpha$ ) cross section is in good agreement with evaluations of cross-section literature (1-3), but the cross section for production of <sup>22</sup>Ne by (n,np) and (n,d) reactions is, surprisingly, ten times the (n,2n) cross section producing 2.6-year <sup>22</sup>Na. The neon extracted from Mg metal was isotopically different from the neon extracted from the magnesium minerals forsterite (Mg<sub>2</sub>SiO<sub>4</sub>) and enstatite (MgSiO<sub>3</sub>), due partly to atmospheric neon contamination in the Mg metal and partly to slight differences in the neutron energy spectrum seen by the Mg-metal sample and the mineral samples. The cross sections given in Table 2 for production of neon isotopes from natural Mg are in excellent agreement with previous measurements at 14.7 MeV (4).

Xenon analyses were performed on samples of CsCl and Ba(NO<sub>3</sub>)<sub>2</sub>. Cross sections given in Tables 3 and 4 appear to be systematically high (by 20-70%) compared to published data, suggesting an error in our calculation of xenon abundances from our isotope dilution data. We are currently reviewing the data to determine whether such an error exists. Notwithstanding this uncertainty, our measured production rate for <sup>130</sup>Xe is much too low to account for the undercalculation of cosmogenic <sup>130</sup>Xe production rates in lunar samples (6,7), confirming Reedy's (8) conclusion that the <sup>130</sup>Ba(n,p) reaction could not account for this discrepancy.

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 Table 1: Production cross sections for neon by 14.5 MeV neutrons on  $^{23}\text{Na}$ :

Product	Cross section (mb)		Principal reactions
	this work	Ref. (1-3)	
$^{20}\text{Ne}$	151±8	150(±25)	$^{23}\text{Na}(n,\alpha)^{20}\text{F}$
$^{21}\text{Ne}$	5.7±0.4	--	$^{23}\text{Na}(n,t)^{21}\text{Ne}$
$^{22}\text{Ne}$	330±17	--	$^{23}\text{Na}(n,np)^{22}\text{Ne}$
			$^{23}\text{Na}(n,d)^{22}\text{Ne}$
$^{22}\text{Na}(2.6a)$	--	32(±10)	$^{23}\text{Na}(n,2n)^{22}\text{Na}$

 Table 2: Production cross sections for neon by 14.5 MeV neutrons on natural magnesium:

Product	Cross section (mb)		Principal reactions
	this work	Ref. (4)	
$^{20}\text{Ne}$	91±5	94±8	$^{24}\text{Mg}(n,n\alpha)^{20}\text{Ne}$
$^{21}\text{Ne}$	150±8	152±12	$^{24}\text{Mg}(n,\alpha)^{21}\text{Ne}$
$^{22}\text{Ne}$	13.4±0.7	13±2	$^{25}\text{Mg}(n,\alpha)^{22}\text{Ne}$
			$^{26}\text{Mg}(n,n\alpha)^{22}\text{Ne}$

 Table 3: Production cross sections for xenon by 14.5 MeV neutrons on  $^{133}\text{Cs}$ :

Product	Cross section (mb)		Principal reactions
	this work	Ref. (1)	
$^{130}\text{Xe}$	2.6±0.3	1.5(±0.5)	$^{133}\text{Cs}(n,\alpha)^{130}\text{I}$
$^{132}\text{Xe}$	1900±100	1600(±100)	$^{133}\text{Cs}(n,2n)^{132}\text{Cs}$

 Table 4: Production cross sections for xenon by 14.5 MeV neutrons on natural barium:

Product	$\sigma$ (mb)	Principal reactions	Cross section (mb)	
			Ref. (5)	Ref. (5) x $F_i$
$^{129}\text{Xe}$	1.82±0.09	$^{130}\text{Ba}(n,2n)^{129}\text{Ba}$ } $^{130}\text{Ba}(n,np)^{129}\text{Cs}$ }	1371±70	1.45±0.08
$^{130}\text{Xe}$	0.034±0.002	$^{130}\text{Ba}(n,p)^{130}\text{Cs}$		
$^{131}\text{Xe}$	1.97±0.10	$^{134}\text{Ba}(n,n\alpha)^{130}\text{Xe}$		
		$^{132}\text{Ba}(n,2n)^{131}\text{Ba}$	1574±100	1.59±0.08
		$^{134}\text{Ba}(n,\alpha)^{131}\text{Xe}$		
$^{132}\text{Xe}$	0.41±0.02	$^{135}\text{Ba}(n,\alpha)^{132}\text{Xe}$		
		$^{136}\text{Ba}(n,\alpha)^{132}\text{Xe}$		
		$^{132}\text{Ba}(n,p)^{132}\text{Cs}$		
$^{134}\text{Xe}$	0.35±0.02	$^{137}\text{Ba}(n,\alpha)^{134}\text{Xe}$		
		$^{138}\text{Ba}(n,n\alpha)^{134}\text{Xe}$		

$F_i$  = fractional abundance of target isotope in natural barium:  $F_{130}=0.00106$ ,  $F_{132}=0.00101$