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KRYPTON

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KRYPTON

Element.[1] Krypton, symbol Kr, is a chemical element of the Helium Group. The chemical atomic weight on the ^{12}C scale is 83.797. In air the relative abundance of each of the major isotopes is: 78 (0.354), 80 (2.27), 82 (11.56), 83 (11.55), 84 (56.90) and 86 (17.37) mole %. The relative cosmic abundances of the isotopes are assumed to be the same as the terrestrial.[2] The ground state electron configuration of the krypton atom is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6$ and the atomic number (z) = 36. Like the other elements of the He group, krypton is placed in the Periodic Table between a halogen (Br) of group VII and an alkali metal (Cs), i.e., between a highly electronegative element and a highly electropositive element. Since Kr, Xe and Rn form some chemical compounds and since several compounds of xenon contain the noble-gas atom in the +8 oxidation state, it is probably appropriate to represent the Helium Group as Group VIII.

Discovery.[3] Krypton was discovered on May 31st, 1898, by Sir William Ramsay and M. W. Travers when they saw new lines in the emission spectrum of the less volatile fractions of liquified air supplied by W. Hampson. The fraction was obtained by boiling off oxygen and nitrogen and the gas proved to be monatomic and to have a density of about 40 (oxygen 16).

It was evidently one position lower in the periodic table than argon. It was named "krypton" from the Greek for "the hidden one".

Origin.[1] Most krypton is primordial in origin. It is probable that in the primordial synthesis of krypton, the most abundant natural isotope, ^{84}Kr, derived from ^{84}Br which undergoes β decay with a half life of about 32 minutes. The radioactive isotopes of masses: 76, 77, 79, 81, 83*m* (metastable ^{83}Kr), 85, 87, 88, 90, 92, 93, 94, 95, and 97 are formed in nuclear reactors but ^{85}Kr is the most important and is the only radioactive isotope with a half life greater than 3 hours. Some isotopes have also been generated in particle accelerators: 81 (^{81}Rb *n,p*), 83 (^{83}Br *p,n* and ^{83}Rb *n,p*), 85*m* (^{85}Br *p,n*), 87 (^{87}Br *p,n*), 88 (^{88}Br *p,n*).

Occurrence.[1] Traces of krypton occur in minerals and meteorites but the usual commercial source is the atmosphere, of which it constitutes 1.14 ppm by volume. Most of the krypton occurring in rocks is found in igneous rocks. Slow neutron fission of uranium produces krypton isotopes, including ^{85}Kr, and the concentration of this isotope in the atmosphere is presently (1973) increasing. Thus the concentration of ^{85}Kr in the air in Cleveland, Ohio, U.S.A., has increased[4] from ca. 8 pCi/m^3 in 1963 to greater than 14 pCi/m^3 in 1970. The estimated abundance of krypton in the earth's crust, including air and oceans is 1.9×10^{-8} weight %. The cosmic abundance is estimated to be 51 per 10^6 atoms of silicon. Recent analyses of lunar material have included $^{84}Kr/^{83}Kr$ ratio determinations and are consistent with the krypton in many lunar surface materials having its origin in the solar wind.[5]

Physical Properties.[1] Krypton is colourless and odorless. The principal physical properties of the gas are given in Table 1. In ascending the Helium Group in the Periodic Table, the atoms become steadily bigger as well as heavier. This is simply a consequence of repulsions of the increasingly numerous electrons surrounding the nucleus, which is almost a point charge repository of the protons. The outermost electrons of krypton ($4s^2$ and $4p^6$) experience a lower attraction towards the nucleus than do the $3s^2$ and $3p^6$ electrons of argon, *i.e.*, the effective nuclear charge of krypton is smaller than in the argon case. Accordingly the outermost electrons of krypton are less firmly bound than in the case of argon. Therefore not only is Kr bigger than Ar but the polarizability (which is a measure of the distortion in the electron clouds produced by other charged bodies) is greater than that of argon and the first ionization potential of Kr (13.999 eV) is less than that of Ar (15.759 eV). Although comparison of the physical properties of krypton with those of the other gases of the He group does express the mass of the atom, the size and polarizability of the atom are of greater significance. The greater polarizability of krypton is responsible for the greater departure from ideal gas behaviour than for He, Ne and Ar. Also, the same feature is responsible for the greater solubility of Kr, compared with the lighter gases, in liquids, and its more ready adsorption, enclathration and encapsulation (see below).

Gas compressibility investigations on krypton have been carried out in two independent laboratories.[1] The Beattie-Bridgemann equation of state for krypton is

$$pV = RT + [(RTB_0 - A_0 - Rc/T^2)/V] + [(-RTB_0b + A_0a - RB_0c/T^2)/V^2] + [(RB_0bc/T^2)/V^3]$$

with $R = 0.08206$, $A_0 = 2.4230$, $a = 0.02865$, $B_0 = 0.05261$, $b = 0$, $c = 14.89\times10^{-4}$

Recommended values of the critical constants, which are based on the most reliable experimental data, are given in the Table.

Liquid krypton has a vapour pressure of ~2 mm Hg at liquid nitrogen temperature and a normal boiling point of 119.80°K. The enthalpy of vapourization at 119.8°K is 2,158 Cal mole^{-1} which compares with 1,557.5 and 3,020 for Ar and Xe, respectively.

Solid krypton, like the other gases of the group, has a face-centred cubic crystal lattice (helium also exhibits close-packed hexagonal forms). The zero point energy for solid Kr (0°K) is 140 cal mole^{-1}. The classical theory, molar volume of the solid at 0°K, V_0, is within experimental error, equal to the experimental molar volume of the face-centred cubic crystal, for which $a = \sqrt{2}\, r_m$, r_m being the Lennard-Jones potential-minimum interatomic distance. Measurements of the hardness and the coefficient of friction of solid krypton show that both the hardness and the coefficient of friction decrease with increasing temperature, the latter having a value of 0.75 at 30°K and ~0.6 at 90°K. The maximum hardness measured was 26×10^6 dynes cm^{-2}.

<u>Adsorption, Clathrates, and Encapsulation.</u>[1,6] (see <u>Argon</u> for a historical note on clathrates). There is a linear relationship between the polarizability of Helium Group atoms and the heat adsorption on an active

surface (e.g. charcoal). There is also abundant evidence to support a dependence upon polarizability, for the enclathration of the gases in water, hydroquinone or other host cages and for their encapsulation in zeolites. The polarizability, α, determines the London dispersion energy, which is the dominant energy term in these interactions. J. H. van der Waals has given a statistical-mechanical theory for clathrates (see Argon).

The molar heat of interaction of krypton with water to form the water clathrate of composition 8 Kr·46 H_2O is 6.5 kcal $mole^{-1}$, which is comparable to the molar enthalpy of adsorption of Kr on charcoal. The krypton hydrate is obtained by maintaining, at 0°C, a pressure of gas in excess of 14.5 atmospheres (which is the invariant decomposition pressure at 0°C). The gas atoms occupy 'cages' in a pseudo-ice water lattice (see Group 0, elements of). 'Double hydrates' can also be made in which krypton is mixed with water and some other species such as acetic acid, chlorine, chloroform or carbon tetrachloride. A double hydrate of Kr, acetone and water has been prepared at -30°C with a gas pressure of 30 atmospheres. The presence of krypton (or heavier gases) will often enhance the stability of a clathrate, in which case the krypton (or other gas) is called a "help gas". Hydroquinone, phenol and related materials readily form clathrates with the heavier He-group gases. The krypton β-hydroquinone clathrate may be prepared as first made, by adding krypton gas (at 20 atmospheres) to a solution of hydroquinone in water at 95°C, the solution being allowed to cool over a 12 hr period. This preparation yields compositions $[C_6H_4(OH)_2]_3 \cdot 0.67$ Kr to $[C_6H_4(OH)_2]_3 \cdot$ 0.74 Kr. Somewhat lower concentrations (25% of theoretical) of krypton

in the host lattice are obtained if the molten β-hydroquinone is allowed to freeze over a 72 hr period under a pressure of 60 atmospheres of krypton. The β-hydroquinone clathrate has been used as a means of retaining ^{85}Kr. ΔH (host lattice (β-form)$_{(c)}$ + $Kr_{(g)}$ → Kr β-hydroquinone clathrate) has been determined to be -6.3 kcal mole^{-1}. The phenole clathrate 2.14 $Kr \cdot 12C_6H_5OH$ is more energetically favourable with an analogous ΔH of -9.0 kcal mole^{-1}. Mössbauer studies, using ^{83}Kr-hydroquinone clathrate absorber indicate sticky collisions of Kr atoms with the β-hydroquinone cavity walls below 150°K but establish that the krypton atoms are essentially in spherical sites -- single resonances only are observed.

Encapsulation of krypton in zeolites is similar to the trapping of the gases in clathrates, but no simple stoichiometry has been established (see Group 0, elements of). Pore and channel size in the synthetic zeolites can be controlled by varying the cation type. The most effective pore diameter for krypton atoms is ~4.0 Å. For synthetic zeolite Type A (K/Na ratio 92:8) 21.6 g of krypton have been encapsulated per 100 g of zeolite. The initial encapsulation pressure, at 350°C, was 4300 atmospheres. This zeolite shows very slow loss of krypton at room temperature, the retention after 30 days being 20.1 g Kr/100 g zeolite. Encapsulation promises to be excellent for ^{85}Kr storage.

Chemical Properties.[6] Since the energy required to remove electrons from a krypton atom is greater than for the related process for xenon (e.g. the first ionization potentials of Kr and Xe are 13.999 and 12.1 eV, respectively) it is much more difficult to involve Kr in chemical bonding than it is xenon. The only known krypton compounds which have

been prepared in macroscopic quantities to this time are krypton difluoride and complex salts, e.g., $[KrF]^+[SbF_6]^-$ and $[KrF]^+[Sb_2F_{11}]^-$, derived from it. Krypton difluoride is thermodynamically unstable with respect to the elements, the total bond energy for the molecule being 23 kcal $mole^{-1}$, whereas that of the fluorine molecule itself is 38 kcal $mole^{-1}$. Krypton difluoride is therefore a more potent oxidizer than gaseous, elemental fluorine itself. The oxidizing power of krypton difluoride is of course an expression of the affinity of the oxidized krypton in KrF_2 for electrons and is a measure of the difficulty of involving krypton in compound formation.

Laboratory Preparation. The low concentration of krypton in air renders laboratory preparation impracticable. The gas may be obtained in high purity from many large scale processors of liquid air. For special needs, e.g., as ^{85}Kr source, a zeolite or phenol clathrate can be used to encapsulate the gas which may be liberated by heating or dissolution.

Production. Following the liquifaction and crude separation of liquid air, krypton and xenon remain with the oxygen. This fraction is re-distilled to concentrate the noble gases to a few per cent. These gases are then adsorbed on to silica gel, desorbed and separated by fractional distillation. Krypton is usually finally treated by passing it over hot titanium. ^{85}Kr ($t_{1/2}$ = 10 yrs) will be increasingly important as nuclear reactors become more numerous. All other radio-isotopes of krypton decay in a few days. Zeolites (see above) promise to be valuable in the separation and storage of this potentially dangerous atmospheric pollutant.

Analysis. The gas is usually analysed qualitatively and quantitatively by mass spectrometry, although gas chromatography is also used. If these facilities are not availabe the emission spectrum of the gas from a discharge tube may be used to characterize it (see the Table). ^{85}Kr may be conveniently monitored with a scintillation counter, after concentrating the gas by dissolution in an organic solvent.[4]

Uses. Krypton is used mainly for light-producing devices. The higher atomic weight of krypton causes it to be a superior gas to argon for electric lamps, since the tungsten filament evapourates less readily in the Kr atmosphere -- consequently the lamp lasts longer. Krypton electric arc lamps are used for high intensity light production -- as in airport runway designation. Krypton ion lasers are particularly valuable for the red and yellow regions of the visible spectrum, the principal lines being (relative intensities in parentheses): 799.3 (30), 793.1 (10), 752.5 (100), 676.4 (120), 647.1 (500), 568.2 (150), 530.9 (200), 520.8 (70), 482.5 (30), 476.2 nm (50). Radioactive ^{85}Kr, enclosed with phosphors in a glass envelope provides a long-lived but slowly diminishing light. Its major application is in leak detection in sealed containers and in the monitoring the thickness of sheets of metals, plastics and other materials. Because the gas is rather soluble in body fluids but is not permanently retained, ^{85}Kr is valuable in physiological and medical investigations.

Economic Aspects.[1] Since, at this time, krypton is always returned to the atmosphere, the supply of krypton is simply determined by the efforts made to extract it from liquid air and more could be extracted to meet

foreseeable demands. ^{85}Kr production will increase markedly as nuclear power plants increase in numbers and since this must be scrubbed out of the effluent gases, much krypton will become available from this source.

Krypton Compounds.[6,7] Following the discovery of true compounds of xenon in 1962, efforts were quickly made to prepare compounds of krypton. In early 1963, von Grosse and his colleagues prepared a fluoride of krypton by electric discharge of a krypton/fluorine mixture at -188°. This was initially thought to be the tetrafluoride but subsequent work has shown it to be KrF_2. The KrF radical was subsequently produced in crystalline KrF_2 by γ irradiation. To this time (1972) the difluoride is the only binary compound to have been prepared in macroscopic quantities and the only other known krypton compounds are the KrF^+ salts,[8] $KrF^+MF_6^-$ (M = Sb, Au) and $KrF^+Sb_2F_{11}^-$, which are derivatives of it.

Krypton (I), Krypton Monofluoride Radical.[6,7] γ Irradiation of crystalline KrF_2 produces a violet coloration which may be caused by the KrF radicals which electron spin resonance studies have shown to be present. It is of interest that reliable calculations[9] have shown that the isolated KrF radical is unbound with respect to ground state Kr and F atoms. Perhaps KrF in KrF_2 is stabilized by the semi-ionic lattice or alternatively involves electronically excited krypton or fluorine.

Krypton (II), Krypton Difluoride.[6,7] The difluoride is a solid at room temperature and sublimes readily to form colourless tetragonal crystals $a_0 = 4.585$, $c_0 = 5.827$ Å, $V_0 = 122.5$ Å^3, $d_c = 3.301$ g cm^{-3}, z = 2, space

group $P4_2/mnm$. The lattice is molecular and contains linear KrF_2 molecules[10] in which the Kr-F interatomic distance = 1.89±0.02 Å. Electron diffraction and high resolution infrared spectroscopy (of the ν_3 band at 589.889 cm^{-1}) have established the linearity of the gaseous molecule, the Kr-F distance being, from the former, 1.889±0.010 Å and 1.875 or 1.867±.002 from the latter. The infrared absorption bands of the vapour are: ν_2, 232.6 (strong), ν_3, 580, 596 (very strong), $\nu_1 + \nu_3$, 1032 cm^{-1}(weak) and from the Raman ν_1 = 449 cm^{-1}. Force constants for the molecule f_r = 2.46, f_{rr} = -0.20 and f_α = 0.21 mdyne $Å^{-1}$ have been interpreted (particularly the negative f_{rr}) by Coulson in terms of the resonance structures $F\text{-}Kr^+F^-$, $F^-Kr\text{-}F^+$ and $\overset{\frown}{F\ Kr\ F}$. Valence-electron photoelectron spectroscopy[11] indicates that the adiabatic first ionization potential may be as low as 13.06 eV but not greater than 13.16 eV. Ionization potentials (vertical) and orbital assignments (given in parentheses) from this study are: 1st, 13.34 ($4\pi_u$); 2nd, 13.90 ($8\sigma_g$); 3rd, 14.37 ($2\pi_g$); 4th, 16.92 ($3\pi_u$); 5th, 17.7 ($5\sigma_u$). ^{19}F nmr spectra of solutions of KrF_2 in anhydrous HF show no exchange with the solvent and yield the chemical shielding values σ_F (relative to molecular F_2) of 374×10^{-6} (4.6 moles/1000 g HF) and 362×10^{-6} (16.4 moles/1000 g HF) at 0°C. The latter solution is a saturated solution. Mössbauer studies support the conclusion, from the nmr data, that there is appreciable electron donation from Kr to F in the Kr-F bonds. The nmr data have been interpreted as indicating a charge on the F atom of -0.45 e in $Kr\text{-}F_2$ and -0.73 e in XeF_2. The Mössbauer data give a quadrupole interaction energy for KrF_2, e^2qQ, = 960±30 mHz; this has been interpreted as indicating approximately 1 e transfer from the krypton atom to its two F ligands.

KrF_2 is thermodynamically unstable ($\Delta H_{f_{(g)}}^{\circ}$ = 14.4±0.8 kcal mole^{-1}) and has the lowest mean thermochemical bond energy of the known fluorides, with a value of 11.7 kcal mole^{-1}. The compound spontaneously decomposes, the decomposition rate for the vapour being approximately 10% per hour. The lattice energy (ΔH sublimation = 9.9 kcal mole^{-1}) helps to stabilize it. The solid can be kept at -78°C. Exact *ab initio* wave mechanical calculations[9] have accounted for the binding of molecular KrF_2, without involvement of krypton orbitals other than 4s and 4p.

KrF_2 is a powerful oxidizer and oxidizes chloride to ClF_3 and ClF_5. It interacts violently with water: $KrF_2 + H_2O \rightarrow Kr + \frac{1}{2}O_2 + 2HF$. Its 1:2 complex with SbF_5 (see below) is a more stable and effective oxidizer.

Laboratory Preparation. The u.v. photolysis of F_2 suspended in a mixture of argon and krypton at 20°K, as described by Turner and Pimentel[6,7] for the first characterization of KrF_2, is only applicable to the synthesis of microscopic quantities of the solid. It is usually prepared by modification of the original electric discharge method, in which Kr/F_2 mixtures are subjected to a discharge from Cu electrodes at -188°C, or by the 10 MeV proton bombardment of Kr/F_2 mixtures in an aluminium container, at ~-150°C, using a cyclotron. In the last method 1-hr irradiation at 5 μa yields ca. 1 g of KrF_2. Claims have been made for quantitative generation of KrF_2 from electric discharge of Kr, CCl_2F_2 mixture in a circulating system which provides for the continuous trapping of KrF_2.[12]

Complexes.[6,7] KrF_2 combines with SbF_5 to form the salts $KrF^+SbF_6^-$ and $KrF^+Sb_2F_{11}^-$. The adduct with AsF_5 is probably also a KrF^+ salt.

The SbF_5 complexes are thermally much more stable than KrF_2. The KrF^+ cation is more strongly bound than KrF_2, the enthalpy for the process $Kr^+_{(g)} + F_{(g)} \rightarrow KrF^+_{(g)}$ being $\geq$ 38 kcal mole^{-1}. Full wave mechanical calculations show KrF^+ (which is isoelectronic with Br-F) to be well bound and predict[9] the stretching frequency to be 621 cm^{-1}, in excellent agreement with the observed value of 626 cm^{-1}. The electron affinity of KrF^+ is ca. 284 kcal mole^{-1}, which requires an unusually stable counter anion. The indicated electron affinity is compatible with the observation that O_2^+ salts are formed ($I(O_2)$ = 281 kcal mole^{-1}) when KrF^+ salts are held in glass containers. The KrF^+ ion is effectively an F^+ source in oxidative reactions,[8] e.g., $KrF^+ + XeOF_4 \rightarrow XeOF_5^+ + Kr$.

Uses. KrF_2 is capable (through its complexes) of generating unusually high oxidation states (e.g. Xe(VIII)) of the elements.

Safety. Since KrF_2 is the least stable and most powerfully oxidizing of the known fluorides it must be handled with great care to avoid loss and damage. Kel F, and teflon are oxidized by it although dry glass and quartz are satisfactory container materials at lower temperatures (<-30°). Sapphire is the best container material.

Table 1. Physical Properties of Krypton[a]

Density of gas, at 0°C and 1 atmosphere, g $liter^{-1}$	3.7493
Triple point, °C	-157.20
Pressure at triple point, mm Hg	548
Boiling point (normal, 1 atmosphere), °C	-153.35
Critical temperature, °C	-63.8
Critical pressure, atmospheres	54.3
Critical density, g cm^{-3}	0.908
Density of liquid, at boiling point, g cm^{-3}	2.413
Density of solid, at triple point, g cm^{-3}	2.826
Density of solid, at 20°K	3.190
Normal volume, $V_N = RT_0[(pV)_1/(pV)_0]$, liter $mole^{-1}$	
(RT_0 = 22.4140 liter $mole^{-1}$)	22.3511
Heat capacity of gas, C_p, at 25°C and 1 atmosphere pressure,	
cal (°K g-mole)$^{-1}$	4.9680
Ratio, C_p/C_v, (0 to 20°C)	1.689
Heat capacities, cal (°K g-mole)$^{-1}$:	
C_s, liquid (117-123°K)	10.7
C_s, solid (113°K)	8.38
C_v, solid (113°K)	5.98
Heat of fusion of solid, at triple point, cal g-$mole^{-1}$	390.7
Heat of vaporization of liquid at normal boiling point,	
cal g-$mole^{-1}$	2158
Velocity of sound in the gas at 0°C and 1 atm pressure,	
m sec^{-1}	213
Refractive index of gas at 0°C and 1 atm. for 5893 Å	1.000427

Magnetic susceptibility, cgs units $(g\text{-mole})^{-1}$		-0.000028
Thermal conductivity:		
of gas at 0°C and 1 atm., cal $(°C\ cm\ sec)^{-1}$		2.09×10^{-5}
of liquid at normal boiling point, cal $(°K\ cm\ sec)^{-1}$		21.3×10^{-5}
Dielectric constant at 25°C and 1 atmosphere		1.000768
Coulour of light emitted by gas discharge		yellow to green
Wavelengths of emission lines for identifying gas (relative intensities in parentheses):		5870.9158 (3000)
		5570.2895 (2000)
		5468.17 (200)
		4362.6423 (500)
		4319.5797 (1000)
		4057.01 (300)
Crystal lattice[b]: face centred cubic at 58°K, a_0 = 5.721 Å		
Atomic radiu, in Å units		
from viscosity data		1.8
from crystal lattice		1.98
Covalent radius,[c] estimated, in Å units		1.11
Ionization potentials, eV:	1st	13.999
	2nd	24.56
	3rd	36.9
	4th	52.5
Electronegativity coefficient (after Pauling)[d]		2.6
Static Polarizability, $Å^3$		2.465
Heat of adsorption on activated charcoal (kcal $g\text{-mole}^{-1}$), at 223°K		5.32

Water solubility:

Solubility, cc gas (STP) per 1000 g water, at 1 atmosphere partial pressure:

Solubility	99.1	75.1	59.4	48.8	41.5	36.4	32.8	30.2	28.5
Temp. (0°C)	0	10	20	30	40	50	60	70	80

Solubility coefficient, S_0, in cc of gas (298.15°K, 1 atm) per 1000 g water, at a gas pressure of 1 atmosphere is given by

$$\log_{10} S_0 = -60.434 + \frac{3410}{T} + 20.5 \log_{10} T$$

(Experimental values of S_0 generally agree within ±0.5% with those calculated from this equation)

References to solubilities in other solvents can be found in (a), Vol. I, pp. 177-178.

(a) Most of the data in this table is drawn from "Argon, Helium and the Rare Gases," G. A. Cook, ed., Vols. I and II, Interscience Publishers, New York and London, 1961.

(b) Crystallographic data from R. W. G. Wyckoff, "Crystal Structures", Interscience Publishers, New York, London, Sydney, 1963, Vol. 1, pp. 10-11.

(c) From estimates given by R. G. Gillespie, in "Noble Gas Compounds," H. H. Hyman, ed., The University of Chicago Press, Chicago and London, 1963, p. 333 and by B.-M Fung (d).

(d) Value derived by B.-M. Fung, J. Phys. Chem., 64, 596 (1965).

References

(1) "Argon, Helium and The Rare Gases," Two Volumes, G. A. Cook, ed., Interscience Publishers, New York, London, 1961, is the most comprehensive reference work on krypton.

(2) A. E. Suess and H. C. Urey, Revs. Mod. Phys., 28, 53 (1956).

(3) "Sir William Ramsey" by Morris, W. Travers, Edward Arnold, London, 1957, is an excellent biography of Ramsey and gives a full account of the discovery of krypton. A full account of the discovery of krypton is also given by E. N. Hiebert in "Noble Gas Compounds," H. H. Hyman, ed., The University of Chicago Press, Chicago and London, 1963.

(4) R. E. Shuping, C. R. Phillips, and A. A. Moghissi, Radiological Health Data Reports, 11, 671 (1970).

(5) Science, 167, No. 39h8, January 30, 1970, a special issue containing the detailed analytical findings on lunar material retrieved by Apollo 11, includes a number of analyses of noble-gas content. The relevance of the findings to cosmological theory and the nature of the solar wind is discussed.

(6) N. Bartlett and F. O. Sladky, 'The Chemistry of Krypton, Xenon and Radon', in Comprehensive Inorganic Chemistry, A. F. Trotman-Dickenson, ed., Pergamon Press, London, July 1963, Vol. 1, Chapter 6.

(7) Gmelin, 'Handbuch der Anorganischen Chemie', Edelgasverbindungen, Vol. 1, 1970.

(8) D. E. McKee, C. J. Adams, A. Zalkin, and Neil Bartlett, J. Chem. Soc., Chem. Comm., 26 (1973).

(9) B. Liu and H. F. Schaefer, III, J. Chem. Phys., 55, 2369 (1971) and P. S. Bagus, B. Liu and H. F. Schaefer III, J. Amer. Chem. Soc., 94, 6635 (1972).

(10) R. D. Burbank, W. E. Falconer and W. A. Sunder, Science, 178, 1285 (1972).

(11) C. R. Brundle and G. R. Jones, J. Chem. Soc., Faraday Trans. 2, 68, 959 (1972) and R. L. DeKock, J. Chem. Phys., 58, 1267 (1973).

(12) H. Meinert and G. Gnauck, Patents: Brit. 1,056,657, Jan. 25, 1967, and Ger. (East), 51,302, Nov. 5, 1966.

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