Xenology: The enigma of xenon in carbonaceous chondrites

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The isotopic composition of the enigmatic xenon component (the so-called Renazzo-type fission xenon, CCF or *X*), which is said to be released from carbonaceous chondrites at temperatures 600 to 1,000°C, is explained in terms of the variation of the isotopic ratios due to a combined effect of mass-fractionation, neutron capture and cosmic-ray irradiation processes, which took place during the early history of the solar system.

INTRODUCTION

Thirteen years ago, REYNOLDS (1963) published a paper entitled *Xenology*, in which he stated that "*xenology* means to us the detailed study of the abundance of Xe isotopes evolved from meteorites by heating or other means and the inferences that can be drawn from these studies about the early history of the meteorites and the solar system. To the classicist *xenology* means study of a strange substance, which is also appropriate". The history of *xenology* dates back to three years earlier, when REYNOLDS (1960a, b) made the suggestion that the carbonaceous chondrite Murray contains a fission xenon component. This idea eventually evolved into the theory that a strange xenon component called Renazzo-type fission xenon (REYNOLDS and TURNER, 1964; FUNK *et al.*, 1967), CCF (PODOSEK *et al.*, 1971) or *X* (MANUEL *et al.*, 1972b) exists in carbonaceous chondrites and it is released at temperatures 600 to 1,000°C (for a complete list of references on this subject, see KURODA *et al.*, 1974, 1975).

The idea of the existence of a strange xenon component in meteorites is reminiscent of the 18th century theory of phlogiston, according to which all combustible bodies were to be regarded as compounds, one of their constituents being phlogiston. According to MANUEL *et al.* (1972b), carbonaceous chondrites contain two isotopically distinct components of xenon, one of them being xenon *X*. Xenon *X* escapes from the meteorites at temperatures 600 to 1,000°C, but its isotopic composition can not be clearly defined. LEWIS *et al.* (1975) have recently re-

ported that they succeeded in isolating the host phase of a xenon *X*-like substance by etching the carbonaceous chondrite Allende with various acids. This was followed by the claim by ANDERS *et al.* (1975) that the progenitor of this strange xenon component may be one of the volatile heavy elements 113 to 115. The theory of ANDERS *et al.* (1975), however, does not explain the origins of the light xenon isotopes, which accompany *X* (BLACK, 1975; CLAYTON, 1975, 1976).

It is more likely that xenon *X* or the Renazzo-type fission xenon, like phlogiston, does not really exist in nature. It is possible to demonstrate this by paying attention to the amounts and the isotopic compositions of not only the xenon fractions released from the meteorites at various temperatures, but also to those of the xenon fractions remaining in the meteorites during stepwise-heating experiments (KURODA, 1976a, b, c). In the present work, this new approach was incorporated into the earlier method of interpretation for the xenon isotope anomalies (KURODA, 1971; KURODA *et al.*, 1974, 1975).

EXPERIMENTAL DATA

The following xenon isotope data were re-examined in the present study: Renazzo data by REYNOLDS and TURNER (1964); Mokoia data by ROWE (1968); Allende data by PHINNEY (1971); Allende and Mokoia data by MANUEL *et al.* (1972a); Murray data by KURODA *et al.* (1974); Murchison data by KURODA *et al.*

Fig. 1. Correlation plot for $^{134}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon fractions obtained from the carbonaceous chondrites Allende and Mokoia.

- : Allende (LEWIS *et al.*, 1975)
- △ : Allende (MANUEL *et al.*, 1972a)
- ▽ : Allende (PHINNEY, 1971)
- : Mokoia (MANUEL *et al.*, 1972a)
- ▣ : Mokoia matrix (ROWE, 1968)
- : Atmospheric xenon (A)
- ◇ : AVCC xenon (V)
- ★ : SABU *et al.*'s trapped xenon (T)

(1975); and Allende data by LEWIS *et al.* (1975).

RESULTS AND DISCUSSION

Figure 1 shows a plot of $^{134}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for Allende and Mokoia. The data points fall on the straightline TX, where T is SABU *et al.*'s trapped xenon (SABU *et al.*, 1974). The slope of the line TX is slightly different from that of the line TM representing the variation of the isotopic ratios by mass-fractionation. The results shown in Fig. 1 are commonly explained by assuming that the xenon fractions released from the meteorites are mixtures of X and a trapped component T (MANUEL *et al.*, 1972b; SABU *et al.*, 1974).

Figure 2 shows a plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for Allende and Mokoia. The data points are scattered and a number of correlation lines such as TX, TL, TX', TX'', etc. can be drawn each through a few data points.

An extension of the line VA connecting the isotopic compositions of AVCC xenon (V) and of the atmospheric xenon (A) to $^{130}\text{Xe} = 0$ leads to the fission mass-yield spectrum for the so-called KURODA-type fission xenon, in which the abundance at mass number 132 is abnor-

Fig. 2. Correlation plot for $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon fractions obtained from the carbonaceous chondrites Allende and Mokoia. Notation is that used in Fig. 1.

mally high (KURODA, 1960). Similarly, an extension of the line TL to $^{130}\text{Xe} = 0$ leads to the fission mass-yield spectrum obtained by LEWIS *et al.* (1975), in which the abundance at mass number 132 is abnormally low. An extension of the line TX to $^{130}\text{Xe} = 0$, on the other hand, leads to the fission mass-yield spectrum for the Renazzo-type fission xenon (REYNOLDS and TURNER, 1964). An extension of the line TX'', which has a positive slope, on the other hand, leads to a fission mass-yield spectrum, in which the abundance at mass number 132 is negative.

Figure 3 shows a plot of $^{131}\text{Xe}/^{132}\text{Xe}$ versus

Fig. 3. Correlation plot for $^{131}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon fractions obtained from the carbonaceous chondrites Allende and Mokoia. Notation is that used in Fig. 1.

Fig. 4. $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon in Allende (MANUEL *et al.*, 1972a). The letter R refers to the xenon, which is retained by the meteorite at the release temperature.

◇: Bulk meteorite (B). L: Xenon in luna fines.

$^{136}\text{Xe}/^{132}\text{Xe}$ for Allende and Mokoia. The data points are again scattered and correlation lines such as TX, TL, TX', TX'', etc., can be drawn each through a number of data points. These results clearly indicate that the experimental data can not be explained in terms of a simple model, such as employed by REYNOLDS and TURNER (1964), ROWE (1968), MANUEL *et al.* (1972b), SABU *et al.* (1974), LEWIS *et al.* (1975) and others.

Figure 4 shows a plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the Allende data obtained by

MANUEL *et al.* (1972a) in stepwise-heating experiments. Note that the isotopic compositions of not only the xenon fractions released at each temperature but also those of the xenon being retained by the meteorite, are plotted here. The isotopic compositions of the xenon fractions released at 200 and 400°C are similar to the atmospheric xenon (A) and hence the isotopic composition (B) of the xenon, which is retained by the meteorite, moves away from the point A. As the temperature is raised above 600°C, the isotopic composition of the xenon,

Fig. 5. $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon in Allende (PHINNEY, 1971).

Fig. 6. $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon in Mokoia. (MANUEL *et al.* 1972a). $\odot$: Lunar fines (PEPIN *et al.*, 1970).

which is remaining in the meteorite, shifts almost horizontally to the left toward the 1,000°C point. The xenon fractions being retained by the meteorite at temperatures above 1,000°C, appear to be two-component mixtures of the xenon fractions, which are released at 1,400°C and 1,600°C. Figure 5 shows a similar plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the Allende data obtained by PHINNEY (1971) in stepwise-heating experiments.

Figure 6 shows a plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the Mokoia data obtained by

MANUEL *et al.* (1972a) in stepwise-heating experiments. The pattern of variation of the isotopic composition is again similar to that seen for Allende, but the data point for the xenon fraction released at 1,000°C deviates upward away from the direction pointing toward X. The Mokoia 1,000°C data point was ignored by MANUEL *et al.* (1972b), but it appears that the fact that this data point shows such a deviation should not be explained away simply as being due to an experimental error. Figure 7 shows a similar plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$

Fig. 7. $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon in Mokoia matrix (ROWE, 1968) $\odot$: Lunar fines (PEPIN *et al.*, 1970).

Fig. 8. $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon in Renazzo (REYNOLDS and TURNER, 1964).

^{132}Xe for the Mokoia matrix data obtained by ROWE (1968) in stepwise-heating experiments. It is interesting to note that the data point for the xenon fraction released at 850°C displays a similar trend which we have noted earlier for the 1,000°C fraction of Mokoia.

Figure 8 shows a plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the Renazzo data obtained by REYNOLDS and TURNER (1964) in stepwise-heating experiments. The data points for the xenon fractions released from Renazzo in the temperature range between 600°C to 1,200°C appear

to fall on a line connecting the 600°C and 800°C data points, which has a very slight negative slope. REYNOLDS and TURNER (1964) have interpreted this trend as being due to the fact that the xenon fractions released from Renazzo contain mixtures of two components of xenon: (a) a trapped component, whose isotopic composition is represented by that of the xenon released at 600°C and (b) a fission component or the so-called Renazzo-type fission xenon, whose isotopic composition lies off-scale far to the lower-right of Fig. 8. The data points for the

Fig. 9. $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon in Murray (KURODA et al., 1974).

Fig. 10. $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the xenon in Murray (KURODA *et al.*, 1975).

xenon fractions retained by the meteorite in the temperature range 400 to 1,100°C appear to fall on this line, but the slope of this correlation line does not point toward the isotopic composition (*T*) of SABU *et al.*'s trapped xenon (SABU *et al.*, 1974). Moreover, it seems that a correlation line with a slope of almost zero can be drawn, if the data point for the xenon released at 500°C is not ignored.

Figure 9 shows a plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the Murray data obtained by KURODA *et al.* (1974). The pattern of variation of the isotopic compositions of the xenon in the bulk sample of Murray during stepwise heating experiments is analogous to that we have seen for Renazzo, except for the fact that the 1,200°C data point lies near the trapped xenon (*T*) of SABU *et al.* (1974).

Figure 10 shows a plot of $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$ for the Murchison data obtained by KURODA *et al.* (1975). The isotopic composition (*B*) of the xenon being retained by the meteorite changes toward the general direction of the data point (*L*) for the bulk lunar fines 10084 (PEPIN *et al.*, 1970).

While it is difficult to explain these variations of the isotopic ratios by introducing the concept of a hypothetical xenon component such as *X* or the Renazzo-type fission xenon, it seems that the experimental data can be interpreted in a more reasonable manner by considering the fact that the isotopic compositions

of the xenon in meteorites can be altered by a combined effect of a) mass-fractionation, b) neutron-capture and c) cosmic-ray irradiation processes which took place in the early history of the solar system (KURODA, 1971). The new interpretation for the general isotope anomalies observed in xenon can be expressed in a mathematical form as

$$(1 + b_{136})(^{i}\text{Xe}/^{136}\text{Xe})_M = (^{i}\text{Xe}/^{136}\text{Xe})_A \cdot$$

$$(1 + f_i) + a_i + b_i + c_i \quad (1)$$

where the subscripts *M* and *A* refer to the meteorites and the atmosphere, respectively; *i* is the mass number; *f_i* is a mass-fractionation factor; *a_i*, *b_i* and *c_i* are the contributions from the processes of neutron capture, fission and spallation, respectively, at mass number *i*; and *b₁₃₆* is the value of *b_i* at mass number 136 (KURODA *et al.*, 1974).

Table 1 shows the isotopic compositions of xenon in a number of carbonaceous chondrites. Since the carbonaceous chondrites contain generally much greater amounts of xenon than ordinary meteorites, the contribution (*b_i*) from the spontaneous fission of ^{244}Pu is expected to be negligibly small and hence in comparing the isotopic compositions of xenon in various carbonaceous chondrites equation (1) may be written in a simplified form as

Table 1. Xenon in carbonaceous chondrites

	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe	^{136}Xe (10^{-12} cc STP/g)
(1) Murray (KURODA <i>et al.</i> , 1974)	0.01508 ± 0.00022	0.01314 ± 0.00018	0.2578 ± 0.0016	3.222 ± 0.022	0.5064 ± 0.0056	2.572 ± 0.008	3.122 ± 0.019	1.1908 ± 0.0075	1.0000	4705
(2) Murchison (KURODA <i>et al.</i> , 1975)	0.01479 ± 0.00019	0.01301 ± 0.00012	0.2569 ± 0.0015	3.302 ± 0.012	0.5073 ± 0.0018	2.557 ± 0.007	3.120 ± 0.014	1.1900 ± 0.0075	1.0000	3971
(3) Renazzo (REYNOLDS and TURNER, 1964)	0.01366 ± 0.00027	0.01271 ± 0.00025	0.2543 ± 0.0018	3.488 ± 0.019	0.4920 ± 0.0047	2.489 ± 0.008	3.059 ± 0.011	1.1805 ± 0.0046	1.0000	1106
(4) Allende (MANUEL <i>et al.</i> , 1972a)	0.0136 ± 0.0003	0.0124 ± 0.0002	0.251 ± 0.002	6.479 ± 0.059	0.479 ± 0.004	2.408 ± 0.018	2.959 ± 0.018	1.163 ± 0.009	1.0000	560
(5) Allende (PHINNEY, 1971)	0.01379 ± 0.00018	0.01219 ± 0.00019	0.2426 ± 0.0013	5.445 ± 0.028	0.4795 ± 0.0019	2.436 ± 0.006	2.990 ± 0.011	1.1668 ± 0.0045	1.0000	332
(6) Allende (LEWIS <i>et al.</i> , 1975)	0.01381 ± 0.00010	0.01199 ± 0.00011	0.2457 ± 0.0005	5.261 ± 0.009	0.4783 ± 0.0009	2.437 ± 0.003	2.982 ± 0.004	1.1679 ± 0.0015	1.000	644
(7) Mokoia (MANUEL <i>et al.</i> , 1972a)	0.0140 ± 0.0002	0.0129 ± 0.0002	0.246 ± 0.002	3.952 ± 0.028	0.485 ± 0.004	2.438 ± 0.016	2.997 ± 0.016	1.166 ± 0.009	1.000	899
(8) Mokoia matrix (ROWE, 1968)	0.01420 ± 0.00009	0.01251 ± 0.00012	0.2460 ± 0.0009	3.945 ± 0.009	0.4828 ± 0.0016	2.454 ± 0.003	2.986 ± 0.009	1.1720 ± 0.0030	1.000	620

$$Q^i = (V^i + \Delta_i) \left\{ 1 + (136 - i) \cdot \mu \right\} \quad (2)$$

where V^i and Q^i are the $^{i}\text{Xe}/^{136}\text{Xe}$ ratios for the AVCC xenon and the xenon found in a sample of meteorite, respectively, and μ is a massfractionation factor expressed in terms of unit mass difference.

One may be able to make a further assumption that $\Delta_{134} \ll V^{134}$ since the abundance of ^{134}Xe is not likely to be altered significantly by the processes of cosmic-ray irradiation and neutron-capture. Hence we have

$$Q^{134} = V^{134} (1 + 2\mu),$$

and

$$\mu = \frac{Q^{134} - V^{134}}{2V^{134}} \quad (3)$$

Table 2 shows the values of μ and Δ_i calculated from equations (2) and (3) for a number of carbonaceous chondrites. In these calculations, the isotopic composition of the xenon in Murray (KURODA *et al.*, 1974) was used for V^i in equations (2) and (3). It is noteworthy that the values of Δ_{131} and Δ_{132} thus calculated are small compared with the values of Q^{131} and Q^{132} , respectively, and these results seem to indicate that the relative abundances of the heavy xenon isotopes ^{131}Xe , ^{132}Xe , ^{134}Xe and ^{136}Xe are altered primarily by the process of mass fractionation, as it was first pointed out by KURODA and MANUEL (1970). Since the abundances of the light isotopes ^{124}Xe , ^{126}Xe and ^{128}Xe are much lower than those of the heavier isotopes, the effect of the cosmic-ray irradiation

and neutron capture processes are expected to be clearly noticeable (KURODA, 1971). The values of Δ_{124} , Δ_{126} , and Δ_{128} are all positive and are not negligibly small compared with the values of Q^{124} , Q^{126} and Q^{128} . The values of Δ_{130} for Allende and Mokoia are also positive and suggest that there is an excess of ^{130}Xe in these meteorites.

According to KURODA (1971), the abundances of ^{124}Xe and ^{126}Xe in carbonaceous chondrites can be altered significantly by the cosmic-ray irradiation (see also KURODA *et al.*, 1974), while both the cosmic-ray irradiation and neutron capture processes may contribute to the alterations of the abundances of ^{128}Xe , ^{130}Xe , ^{131}Xe and ^{132}Xe and hence we have

$$\Delta_{124} = c_{124} \quad (4)$$

$$\Delta_{126} = c_{126} \quad (5)$$

$$\Delta_{128} = c_{128} + a_{128} \quad (6)$$

$$\Delta_{130} = c_{130} + a_{130} \quad (7)$$

$$\Delta_{131} = c_{131} + a_{131} \quad (8)$$

and

$$\Delta_{132} = c_{132} + a_{132} \quad (9)$$

where the values of a_i for $i = 128-132$ are usually about one order of magnitude greater than the values of c_i .

Figure 11 shows the variations of μ and Δ_i for the xenon fractions remaining in Renazzo

Table 2. Values of μ and Δ_i for carbonaceous chondrites. In calculating these values, the isotopic composition of xenon in Murray was used for V^i in equations (2) and (3).

	μ	Δ_{124}	Δ_{126}	Δ_{128}	Δ_{130}	Δ_{131}	Δ_{132}
(1) Renazzo (REYNOLDS and TURNER, 1964)	-0.004325	-0.00064 ± 0.00025	+0.00046 ± 0.00014	+0.0056 ± 0.0021	-0.0013 ± 0.0030	-0.028 ± 0.015	-0.009 ± 0.015
(2) Allende (MANUEL <i>et al.</i> , 1972a)	-0.01167	+0.00070 ± 0.00030	+0.00091 ± 0.00021	+0.0191 ± 0.0021	+0.0087 ± 0.0043	-0.015 ± 0.009	-0.018 ± 0.019
(3) Allende (PHINNEY, 1971)	-0.01008	+0.00060 ± 0.00017	+0.00041 ± 0.00022	+0.0061 ± 0.0014	+0.0039 ± 0.0021	-0.006 ± 0.009	-0.006 ± 0.009
(4) Allende (LEWIS <i>et al.</i> , 1975)	-0.009615	+0.00054 ± 0.00012	+0.00012 ± 0.00001	+0.0083 ± 0.0006	+0.0013 ± 0.0009	-0.012 ± 0.004	-0.021 ± 0.004
(5) Mokoia (MANUEL <i>et al.</i> , 1972a)	-0.01046	+0.00092 ± 0.00024	+0.00118 ± 0.0002	+0.0110 ± 0.002	+0.010 ± 0.004	+0.001 ± 0.018	+0.007 ± 0.019
(6) Mokoia matrix (ROWE, 1968)	-0.007810	+0.00057 ± 0.00010	+0.00046 ± 0.00013	+0.0049 ± 0.0010	+0.000 ± 0.002	-0.016 ± 0.006	-0.039 ± 0.010

Fig. 11. Values of μ and Δ_i for the xenon fractions remaining in Renazzo during the stepwise-heating experiments. These values were calculated from the Renazzo data obtained by REYNOLDS and TURNER (1964).

Fig. 12. Values of μ and Δ_i for the xenon fractions remaining in Mokoia during stepwise-heating experiments. These values were calculated from the data obtained by MANUEL *et al.* (1972a).

during stepwise-heating experiments. While the values of Δ_{131} and Δ_{132} show no significant changes throughout the temperature range between 200 and 1,200°C, the value of μ increases steadily above 700°C and changes to a positive value at 1,000°C. This means that while at temperatures below 1,000°C the heavier isotopes are systematically enriched relative to AVCC, the opposite is true for the xenon fractions remaining at higher temperatures. It is also interesting to note here that an increase in μ is accompanied by marked decreases in the values of Δ_{124} , Δ_{126} , Δ_{128} and Δ_{130} .

Figures 12 and 13 show the variations of μ and Δ_i for the xenon fractions remaining in Mokoia and Allende, respectively, during step-

wise-heating experiments. The isotopic composition of the xenon in Murray (KURODA *et al.*, 1974) was used for V^i in these calculations. The patterns of variations observed for Mokoia and Allende are quite similar to the pattern observed for Renazzo. The xenon fractions with strange isotopic compositions are released from the meteorites in the temperature range 600 to 1,000°C, where the values of μ and Δ_i for the xenon fractions remaining in the meteorites are undergoing marked changes.

The isotopic composition (R^i) of the strange xenon released from a meteorite at a certain temperature is related to that of the xenon originally present (Q^i) and that of the xenon being retained by the meteorite at that tem-

Fig. 13. Values of μ and Δ_i for the xenon fractions remaining in Allende during stepwise-heating experiments. These values were calculated from the Mokoia data obtained by MANUEL *et al.*, (1972a).

perature (P^i) by the equation

$$R^i = \frac{1}{\xi_{136}} \cdot Q^i - \frac{(1 - \xi_{136})}{\xi_{136}} \cdot P^i \quad (10)$$

where $\xi_{136}/(1 - \xi_{136})$ represents the ratio of the amount of ^{136}Xe released to that of ^{136}Xe retained by the meteorite (KURODA, 1976a, b).

The values of P^i and Q^i in equation (10) may be written in the form of equation (2) and hence we have

$$R^i = \frac{1}{\xi_{136}} [(V^i + \Delta_i) \{ 1 + (136 - i) \cdot \mu \} - (1 - \xi_{136}) (V^i + \Delta'_i) \{ 1 + (136 - i) \cdot \mu' \}] \quad (11)$$

for the isotopic compositions of the xenon released from the meteorites.

Rearranging equation (11), we have

$$R^i = V^i \cdot \frac{1}{\xi_{136}} [\nu_i - (1 - \xi_{136}) \cdot \nu'_i] + \left[\frac{1}{\xi_{136}} \cdot \Delta_i \cdot \nu_i - \frac{(1 - \xi_{136})}{\xi_{136}} \cdot \Delta'_i \cdot \nu'_i \right] \quad (12)$$

or

$$R^i = V^i \cdot \nu'' + (\delta_i - \delta'_i) \quad (13)$$

where $\nu_i = 1 + (136 - i) \cdot \mu$,

$$\nu'_i = 1 + (136 - i) \cdot \mu',$$

$$\nu''_i = \frac{1}{\xi_{136}} [\nu_i - (1 - \xi_{136}) \cdot \nu'_i]$$

$$\delta_i = \frac{1}{\xi_{136}} \cdot \Delta_i \cdot \nu_i,$$

and $\delta'_i = \frac{1 - \xi_{136}}{\xi_{136}} \cdot \Delta'_i \cdot \nu'_i$

If the values of μ and μ' are negative and $|\mu| > |\mu'|$, and if the amount of xenon released is much smaller than the amount, which was originally present, or $\xi_{136} \ll 1$, the values of $V^i \cdot \nu''_i$ in equation (13) become much smaller than the values of V^i for the light isotopes ^{128}Xe , ^{126}Xe and ^{124}Xe . At the same time, the values of $(\delta_i - \delta'_i)$ in equation (13) become comparable to or even greater than the values of $V^i \cdot \nu''_i$, if $\Delta_i > \Delta'_i$. This means that the isotopic composition (R^i) of the xenon released from the meteorite appears to be severely mass-fractionated in such a manner that the heavier isotopes are systematically enriched and yet at the same time the relative abundances of the light isotopes ^{128}Xe , ^{126}Xe and ^{124}Xe are also progressively enhanced.

Table 3 shows the relationship between the isotopic compositions of the xenon remaining in Renazzo at 700°C and 800°C and of the xenon released at 800°C. The isotopic composition of the xenon released from Renazzo at 800°C can be calculated from the data shown in Table 3 by the use of equation (13) as shown in Table 4. The values of Δ_i and Δ'_i for the xenon fractions remaining in Renazzo at 700°C and 800°C are very small and hence only approximate values of $(\delta_i - \delta'_i)$ can be obtained. Nevertheless, the values of R^i thus calculated appear to be in excellent agreement with the observed values of the isotopic composition of xenon released

Table 3. Relationship between the isotopic compositions of the xenon remaining in Renazzo at 700°C and 800°C and of the xenon released at 800°C.

	(I) Xenon remaining at 700°C		(II) Xenon remaining at 800°C		(I)-(II) = Xenon released at 800°C		Percentage of the xenon isotopes released at 800°C (a)
	(10 ⁻¹² cc STP/g)	Q^i (Isotopic ratio)	(10 ⁻¹² cc STP/g)	P^i (Isotopic ratio)	(10 ⁻¹² cc STP/g)	R^i (Isotopic ratio)	
¹²⁴ Xe	9.8050	(0.01429)	8.8079	(0.01434)	0.9971	(0.01393)	10.169 (±0.203)
¹²⁶ Xe	8.6421	(0.01260)	7.7662	(0.01264)	0.8759	(0.01223)	10.135 (±0.101)
¹²⁸ Xe	172.2923	(0.2512)	155.0639	(0.2524)	17.2284	(0.2407)	10.000 (±0.070)
¹³⁰ Xe	340.673	(0.4967)	306.647	(0.4991)	34.026	(0.4753)	9.988 (±0.040)
¹³¹ Xe	1714.6728	(2.4997)	1542.5778	(2.5109)	172.095	(2.4040)	10.037 (±0.030)
¹³² Xe	2094	(3.0527)	1884	(3.0666)	210	(2.9334)	10.029 (±0.060)
¹³⁴ Xe	808.8492	(1.1792)	726.0672	(1.1818)	82.7820	(1.1564)	10.235 (±0.082)
¹³⁶ Xe	685.940	(1.0000)	614.353	(1.0000)	71.587	(1.0000)	10.436 (±0.003)

$$(a) \frac{(I) - (II)}{(I)} \cdot 100 = \xi_i \cdot 100.$$

Table 4. Isotopic composition of the xenon released from Renazzo at 800°C.

Mass No. i	Δ_i	ν_i	δ_i	Δ'_i	$\delta_i - \delta'_i$	V^i	ν''_i	$V^i \cdot \nu''_i$	Isotopic composition R^i	
									(Calculated)	(Experimental)
124	0.00051 ±0.00027	0.95556	0.0047 ±0.0025	0.00037 ±0.00027	0.0016 ±0.0025	0.01442	0.84266	0.01215	0.01375 ±0.0025	0.01393
126	0.00036 ±0.00012	0.96296	0.0033 ±0.0011	0.00026 ±0.00012	0.0011 ±0.0011	0.01271	0.86900	0.01105	0.01215 ±0.0011	0.01223
128	0.0044 ±0.0019	0.97038	0.0409 ±0.018	0.0034 ±0.0019	0.0123 ±0.018	0.2543	0.89526	0.2277	0.240 ±0.018	0.2407
130	0.0054 ±0.0039	0.97778	0.0506 ±0.037	0.0045 ±0.0039	0.0126 ±0.037	0.5025	0.92142	0.4630	0.476 ±0.037	0.4753
131	0.0038 ±0.013	0.98149	0.0357 ±0.122	0.0011 ±0.013	0.026 ±0.122	2.543	0.93455	2.377	2.403 ±0.122	2.404
132	-0.0171 ±0.016	0.99259	-0.163 ±0.152	-0.0169 ±0.016	—	3.116	0.94768	2.953	2.953	2.933
134	—	—	—	—	—	1.188	0.97384	1.157	1.157	1.1564
136	—	—	—	—	—	1.0000	1.00000	1.000	1.000	1.0000

from Renazzo at 800°C (REYNOLDS and TURNER, 1964).

Tables 5 and 6 show the results of similar calculations for the xenon released from Mokoia at 750°C (MANUEL *et al.*, 1972a). The agreement between the calculated and observed values of R^i is again excellent. Tables 7 and 8 show the results of similar calculations for the xenon released from Allende at 800°C (MANUEL *et al.*, 1972a). It is interesting to note here that the amount of xenon released was quite small in this case and hence $\xi_i \ll 1$. The isotopic com-

position of the xenon released from Allende at 800°C thus appears as if it contains a severely mass fractionated AVCC xenon with a negative value of $V^i \cdot \nu''_i$ for $i = 124$, while the values of $(\delta_i - \delta'_i)$ for the light isotopes ¹²⁸Xe, ¹²⁶Xr and ¹²⁴Xe are all greater than the values of $V^i \cdot \nu''_i$. It seems that the agreement between the calculated and observed values of R^i is quite reasonable, considering the fact that large uncertainties are associated with the calculations of the values of $(\delta_i - \delta'_i)$.

The isotopic compositions of the strange

Table 5. Relationship between the isotopic compositions of the xenon fractions remaining in Mokoia at 600°C and 750°C, and of the xenon fraction released at 750°C.

	(I) Xenon remaining at 600°C		(II) Xenon remaining at 750°C		(I)-(II) = Xenon released at 750°C		Percentage of the xenon isotopes released at 750°C (a)
	(10 ⁻¹² cc STP/g)	Q ⁱ (Isotopic ratio)	(10 ⁻¹² cc STP/g)	P ⁱ (Isotopic ratio)	(10 ⁻¹² cc STP/g)	R ⁱ (Isotopic ratio)	
¹²⁴ Xe	11.8094	(0.01411)	10.6472	(0.01424)	1.1622	(0.0130)	9.841(±0.151)
¹²⁶ Xe	10.8102	(0.01292)	9.8178	(0.01313)	0.9923	(0.0111)	9.179(±0.165)
¹²⁸ Xe	206.7284	(0.2470)	188.9378	(0.2527)	17.7906	(0.199)	8.606(±0.086)
¹³⁰ Xe	405.3342	(0.4843)	371.094	(0.4964)	34.2402	(0.446)	8.447(±0.066)
¹³¹ Xe	2040.8138	(2.4382)	1864.7852	(2.4944)	176.0286	(1.969)	8.625(±0.066)
¹³² Xe	2488.9026	(2.9736)	2275.0578	(3.0431)	213.8448	(2.392)	8.592(±0.039)
¹³⁴ Xe	975.6020	(1.1656)	880.2122	(1.1774)	95.3898	(1.067)	9.778(±0.083)
¹³⁶ Xe	837.	(1.0000)	747.6	(1.0000)	89.4	(1.0000)	10.681(±0.049)

$$(a) \frac{(I) - (II)}{(I)} \cdot 100 = \xi_i \cdot 100$$

Table 6. Isotopic composition of the xenon released from Mokoia at 750°C.

Mass No. i	Δ_i	ν_i	δ_i	Δ'_i	$\delta_i - \delta'_i$	ν^i	ν''_i	$\nu^i \cdot \nu''_i$	Isotopic composition R ⁱ	
									(Calculated)	(Experimental)
124	0.00108 ±0.0002	0.87304	0.0088 ±0.0016	0.00019 ±0.0002	0.0073 ±0.0016	0.01508	0.37559	0.00566	0.0130 ±0.0016	0.0130
126	0.00131 ±0.0002	0.89420	0.0110 ±0.0017	0.00077 ±0.0002	0.0049 ±0.0017	0.01314	0.48001	0.00631	0.0112 ±0.0017	0.0111
128	0.0120 ±0.002	0.91536	0.103 ±0.017	0.0068 ±0.002	0.049 ±0.017	0.2578	0.58403	0.1506	0.200 ±0.017	0.199
130	0.0107 ±0.002	0.93652	0.094 ±0.035	0.0073 ±0.002	0.035 ±0.035	0.5064	0.68795	0.3484	0.383 ±0.035	0.383
131	0.0024 ±0.018	0.94710	0.0212 ±0.16	-0.0054 ±0.18	0.0642 ±0.16	2.5720	0.74000	1.903	1.967 ±0.16	1.969
132	-0.0169 ±0.019	0.95768	-0.1515 ±0.17	-0.0088 ±0.019	-0.0796 ±0.17	3.1220	0.79206	2.473	2.393 ±0.17	2.392
134	—	—	—	—	—	1.1908	0.89598	1.067	1.067	1.067
136	—	—	—	—	—	1.0000	1.00000	1.000	1.000	1.000

Table 7. Relationship between the isotopic compositions of the xenon remaining in Allende at 600°C and 800°C and of the xenon released at 800°C.

	(I) Xenon remaining at 600°C		(II) Xenon remaining at 800°C		(I)-(II) = Xenon released at 800°C		Percentage of the xenon isotopes released at 800°C (a)
	(10 ⁻¹² cc STP/g)	Q ⁱ (Isotopic ratio)	(10 ⁻¹² cc STP/g)	P ⁱ (Isotopic ratio)	(10 ⁻¹² cc STP/g)	R ⁱ (Isotopic ratio)	
¹²⁴ Xe	7.0003	(0.0139)	6.8969	(0.0139)	0.1035	(0.0121)	1.471(±0.049)
¹²⁶ Xe	6.3638	(0.0126)	6.2826	(0.0127)	0.0813	(0.0095)	1.273(±0.040)
¹²⁸ Xe	128.128	(0.2540)	126.640	(0.2554)	1.488	(0.174)	1.161(±0.027)
¹³⁰ Xe	243.61	(0.4830)	240.75	(0.4856)	2.86	(0.334)	1.174(±0.021)
¹³¹ Xe	1218.59	(2.416)	1203.78	(2.428)	14.81	(1.732)	1.215(±0.019)
¹³² Xe	1492.69	(2.9596)	1474.38	(2.974)	18.31	(2.142)	1.226(±0.016)
¹³⁴ Xe	586.75	(1.1634)	578.04	(1.1659)	8.71	(1.019)	1.484(±0.023)
¹³⁶ Xe	504.35	(1.000)	495.8	(1.000)	8.55	(1.000)	1.695(±0.022)

$$(a) \frac{(I) - (II)}{(I)} \cdot 100 = \xi_i \cdot 100$$

Table 8. Isotopic composition of the xenon released from Allende at 800°C.

Mass No. i	Δ_i	ν_i	δ_i	Δ'_i	$\delta_i - \delta'_i$	ν_i	ν''_i	$\nu_i \cdot \nu''_i$	Isotopic composition R^i R^i (Calculated)(Experimental)	
124	0.00104 ± 0.0002	0.85996	0.0528 ± 0.0102	0.00068 ± 0.0002	0.0183 ± 0.0102	0.01508	-0.01652	-0.000249	0.018 ± 0.010	0.0121
126	0.00113 ± 0.0002	0.88330	0.0589 ± 0.0104	0.00100 ± 0.0002	0.0070 ± 0.0104	0.01314	0.15280	0.00201	0.009 ± 0.010	0.0095
128	0.0224 ± 0.002	0.90664	1.198 ± 0.107	0.0201 ± 0.002	0.130 ± 0.107	0.2578	0.32212	0.08304	0.213 ± 0.107	0.174
130	0.0130 ± 0.004	0.92298	0.7079 ± 0.218	0.0117 ± 0.004	0.072 ± 0.218	0.5064	0.49145	0.2489	0.321 ± 0.218	0.334
131	-0.007 ± 0.009	0.94165	-0.389 ± 0.500	-0.010 ± 0.009	0.161 ± 0.500	2.5720	0.57640	1.483	1.644 ± 0.500	1.732
132	-0.017 ± 0.019	0.95332	-0.956 ± 1.06	-0.019 ± 0.019	0.104 ± 1.06	3.1220	0.66077	2.063	2.167 ± 1.06	2.142
134	—	—	—	—	—	1.1908	0.83068	0.989	0.989	1.019
136	—	—	—	—	—	1.0000	1.00000	1.000	1.000	1.000

Table 9. Relationship between the isotopic compositions of the xenon in Allende 3CS1 and Allende 3CS2.

Mass No. i	(I) Xenon in Allende 3CS1 (10^{-10} cc STP/g)	Q^i (Isotopic ratio)	(II) Xenon which escaped during etching (10^{-10} cc STP/g)	P^i (Isotopic ratio)	(III) = (I) - (I) Xenon found in Allende 3CS2 (10^{-10} cc STP/g)	R^i (Isotopic ratio)	Percentages of the xenon isotopes which were not lost during etching (a)
^{124}Xe	9.3942	(0.014000)	7.80518	(0.01425)	1.58902	(0.01293)	16.915(± 0.250)
^{126}Xe	8.3030	(0.01238)	7.0651	(0.01289)	1.23788	(0.01007)	14.909(± 0.255)
^{128}Xe	162.430	(0.2425)	140.113	(0.2558)	22.3170	(0.1815)	13.740(± 0.079)
^{130}Xe	320.614	(0.4780)	279.4372	(0.5101)	41.1768	(0.3349)	12.843(± 0.080)
^{131}Xe	1624.30	(2.4215)	1409.515	(2.5728)	214.785	(1.7471)	13.223(± 0.071)
^{132}Xe	1984	(2.9577)	1726	(3.1505)	258	(2.0986)	13.004(± 0.060)
^{134}Xe	778.323	(1.1603)	653.632	(1.1931)	124.691	(1.0143)	16.020(± 0.060)
^{136}Xe	670.790	(1.0000)	547.853	(1.0000)	122.937	(1.0000)	18.327(± 0.085)

$$(a) \frac{(I) - (II)}{(I)} \cdot 100 = \xi_i \cdot 100$$

xenon obtained by LEWIS *et al.* (1975) from Allende in acid-etching experiments are similar to that of the xenon released from the meteorite at 800°C. Tables 9 and 11 show the relationships between the isotopic compositions of the xenon in Allende 3CS1, 3CS2 and 3CS4. Tables 10 and 12 show that the isotopic compositions (R^i) of the xenon found in 3CS2 and 3CS4, respectively, calculated by equation (13) also agree with experimental values reasonably well.

CONCLUSION

It seems that the existing xenon isotope data can be explained satisfactorily by the theory that the xenon isotopic ratios are altered

by a combined effect of mass-fractionation, neutron capture and cosmic-ray irradiation processes, which took place during the early history of the solar system (KURODA, 1971; KURODA *et al.*, 1974, 1975; KURODA, 1967a, b). The carbonaceous chondrites appear to contain three different types of xenon: (a) the atmospheric xenon, most of which is released from the meteorites at temperatures below 400°C, (b) the xenon, which contains excess light isotopes relative to the AVCC xenon and which escapes from the meteorites in the temperature range 600° to 1,000°C, and (c) the AVCC-type xenon, which is released usually at higher temperatures. In the meteorites such as Renazzo, Mokoia and Allende, the xenon components (a), (b) and (c) are bound to the mineral lattices with suc-

Table 10 Isotopic composition of the xenon in Allende 3CS2. The values of Δ_i , ν_i and δ_i were calculated from the isotopic composition of the xenon in 3CS1 and the values of Δ'_i and δ'_i were calculated from that of the xenon, which escaped from 3CS1 during etching (see Table 9).

Mass No. i	Δ_i	ν_i	δ_i	Δ'_i	δ'_i	ν_i	ν''_i	$\nu_i \cdot \nu''_i$	Isotopic composition of the xenon in Allende 3CS2 R^i (Calculated) (Experimental)	
124	0.00160 ± 0.0005	0.86008	0.0117 ± 0.0037	-0.00054 ± 0.0005	~ 0	0.01442	0.12173	0.0018	0.0135 ± 0.0037	0.0129 ± 0.0002
126	0.00115 ± 0.0003	0.88340	0.0087 ± 0.0022	-0.0009 ± 0.0003	~ 0	0.01271	0.26813	0.0034	0.0121 ± 0.022	0.0101 ± 0.0002
128	0.0120 ± 0.0024	0.90672	0.093 ± 0.019	-0.00287 ± 0.0024	~ 0	0.2543	0.41452	0.1054	0.1984 ± 0.019	0.1815 ± 0.0010
130	0.0107 ± 0.005	0.93004	0.085 ± 0.039	+0.00113 ± 0.005	~ 0	0.5025	0.56086	0.2818	0.367 ± 0.005	0.335 ± 0.002
131	0.0268 ± 0.002	0.94170	0.216 ± 0.016	+0.0025 ± 0.002	~ 0	2.543	0.63403	1.612	1.828 ± 0.016	1.748 ± 0.009
132	-0.013 ± 0.020	0.95336	-0.106 ± 0.163	+0.0078 ± 0.020	~ 0	3.116	0.70726	2.204	2.098 ± 0.163	2.099 ± 0.020
134	—	—	—	—	—	1.188	0.85360	1.014	1.014 ± 0.050	1.014 ± 0.004
136	—	—	—	—	—	1.000	1.00000	1.000	1.000	1.000

Table 11. Relationship between the isotopic compositions of the xenon in Allende 3CS1 and Allende 3CS4.

Mass No. i	(I) Xenon in Allende 3CS1		(II) Xenon which escaped during etching		(III) = (I)-(II) Xenon found in Allende 3CS4		Percentage of the xenon isotopes which were not lost during etching (a)
	(10^{-10} cc STP/g)	Q^i (Isotopic ratio)	(10^{-10} cc STP/g)	P^i (Isotopic ratio)	(10^{-10} cc STP/g)	R^i (Isotopic ratio)	
^{124}Xe	9.3942	(0.01400)	8.4154	(0.01420)	0.97883	(0.01247)	10.420(± 0.229)
^{126}Xe	8.3030	(0.01238)	7.6473	(0.01291)	0.65570	(0.008351)	7.897(± 0.373)
^{128}Xe	162.430	(0.2425)	150.6086	(0.2542)	11.8214	(0.1505)	7.278(± 0.091)
^{130}Xe	320.614	(0.4780)	299.287	(0.5052)	21.3270	(0.2716)	6.652(± 0.059)
^{131}Xe	1624.30	(2.4215)	1511.70	(2.5520)	112.5994	(1.4340)	6.932(± 0.060)
^{132}Xe	1984	(2.9577)	1849.36	(3.1220)	134.64	(1.7147)	6.786(± 0.055)
^{134}Xe	788.323	(1.1603)	702.9785	(1.1867)	75.3445	(0.9595)	9.680(± 0.071)
^{136}Xe	670.790	(1.0000)	592.268	(1.0000)	78.5220	(1.0000)	11.706(± 0.094)

$$(a) \frac{(I) - (II)}{(I)} \cdot 100 = \xi_i \cdot 100$$

cessively greater forces, and hence they are generally released in that order when the meteorites are heated. The xenon fractions with strange isotopic compositions are released at temperatures 600° to 1,000°C, when the ratio of the amounts of (b) to (a) is rapidly decreasing in the meteorites. The heavier isotopes of xenon are systematically enriched in (b) relative to (c), and hence the xenon released at temperatures 600° to 1,000°C often appears to be severely mass-fractionated in such a manner that the abundances of the heavier isotopes are markedly enhanced. The abundances of the

three lightest isotopes are also enhanced in the xenon fractions released at 600° to 1,000°C, because the release of excess light isotopes from the meteorites occurs in the same temperature range. Further experimental studies along these lines are in progress in our laboratories and the results from these studies will be reported in the near future.

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Table 12. Isotopic composition of the xenon in Allende 3CS4. The values of Δ_i , ν_i and δ_i for Allende 3CS1 used in these calculations are shown in Table 10.

Mass No. i	Δ'_i	ν'_i	δ'_i	ν_i	ν''_i	$\nu_i \cdot \nu''_i$	$\delta_i - \delta'_i$	Isotopic composition of the xenon in Allende 3CS4 R_i (Calculated) (Experimental)	
124	0.00010 ± 0.00005	0.99344	0.000749	0.01442	-0.14582	-0.00210	0.011 ± 0.0037	0.0089 ± 0.0037	0.01247 ± 0.00027
126	0.00027 ± 0.0003	0.99453	0.002025	0.01271	0.04519	0.00057	0.0067 ± 0.0022	0.0073 ± 0.0022	0.00835 ± 0.00039
128	0.0010 ± 0.0024	0.99562	0.00751	0.2543	0.2362	0.06693	0.086 ± 0.019	0.153 ± 0.019	0.151 ± 0.002
130	0.0044 ± 0.005	0.99672	0.03308	0.5025	0.42713	0.2146	0.052 ± 0.005	0.267 ± 0.005	0.272 ± 0.002
131	0.016 ± 0.002	0.99726	0.1204	2.543	0.52264	1.329	0.096 ± 0.016	1.425 ± 0.016	1.434 ± 0.012
132	0.0128 ± 0.020	0.99781	0.0963	3.116	0.61815	1.926	-0.202 ± 0.163	1.724 ± 0.163	1.715 ± 0.014
134	—	—	—	1.188	0.8090	0.9610	—	0.961 ± 0.050	0.960 ± 0.007
136	—	—	—	1.000	1.0000	1.0000	—	1.0000	1.0000

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