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s-PROCESS STUDIES: XENON AND KRYPTON ISOTOPIC ABUNDANCES

DONALD D. CLAYTON AND RICHARD A. WARD
Department of Space Physics and Astronomy, Rice University
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ABSTRACT

We propose an analysis of the *s*-process contributions to the isotopes of xenon and krypton. The object is to aid studies of the possibility that meteorites may contain gas that was carried in presolar grains that were grown in stellar ejecta and that were not degassed prior to incorporation into parent bodies. That model suggests routine interstellar fractionation of *s*-isotopes from *r*-isotopes owing to differential incorporation into dust. We show that a deficiency of *s*-process nuclei cannot yield details of Xe–*X*, but the gross similarities are strong enough to lead one to think that such a deficiency may play a role in a more complicated explanation. We predict the existence of an *s*-rich complement somewhere if fractional separation of this type has played a role in Xe–*X*. We show that the analogous decomposition of krypton is more uncertain, and we call for measurements of neutron-capture cross sections to alleviate these uncertainties.

Subject headings: abundances — meteors and meteorites — nucleosynthesis

I. INTRODUCTION

Xenon is one of the most interesting of elements from a cosmochemical viewpoint. It has nine stable isotopes which appear in varying ratios in different objects, including the well-known extinct-radioactivity anomalies in the meteorites. The interest in xenon has heightened markedly in the past years due to discoveries of isotopic anomalies in meteorites. It appears that the solar system formed without vaporizing all preexisting dust, and that dust carried isotopic anomalies in Ne (Black 1972) and in O (Clayton, Grossman, and Mayeda 1973) that were implanted near sites of nucleosynthesis. Those discoveries motivated us to construct a model of the interstellar medium as a highly fractionated medium, chemically and isotopically, and to attempt to interpret all isotopic anomalies as being the result of enhancement of one phase relative to another in the accumulation processes leading to larger objects. Clayton (1975) examined this possibility for xenon, even going so far as to interpret each of the xenon daughter anomalies from the extinct radioactivities as being due to grains precipitated in expanding supernova envelopes and surviving in the meteorites. Black (1975) took a similar scenario in attempting to interpret the so-called carbonaceous-chondrite fission (CCF) xenon as being a special *r*-process nucleosynthesis that was trapped in grains forming before mixture with the interstellar gases. Manuel, Hennecke, and Sabu (1972) found that light isotopes ^{124}Xe and ^{126}Xe correlate with strange unshielded xenon, and they conjectured that it was due to the injection of *p*-process isotopes along with *r*-isotopes from a local supernova. Cameron and Truran (1977) took a similar view. Clayton (1975) constructed his scenario with supernova-dust carriers from earlier galactic supernovae, and Clayton (1976) used that scenario and his estimates of the *p*-process yields of the four lightest isotopes to show that this correlation would have major effects on the estimation of the fission yield spectrum of the putative parent of the strange CCF Xe. If this emerging picture proves to be correct, the xenon anomalies assume an even larger interest than they already possessed as probes of the formation and evolution of the solar system. It becomes important to analyze the yields of specific nucleosynthesis processes to the xenon isotopes. We provide that discussion here. Its potential significance has been augmented by more recent discoveries of anomalies in unshielded isotopes of Nd and Ba (McCulloch and Wasserburg 1978).

II. XENON

Because Clayton's (1976) discussion was restricted to variations in the concentration of the specific component $\boldsymbol{X}$ (Manuel *et al.*), he defined $\boldsymbol{X} = \boldsymbol{P} + \boldsymbol{R}$, where the vector $\boldsymbol{P} = (^{124}\mathrm{Xe}_p, {}^{126}\mathrm{Xe}_p, {}^{128}\mathrm{Xe}_p, {}^{130}\mathrm{Xe}_p)$ represents the *p*-process yields of those isotopes shielded from the *r*-process and from fission production, and where $\boldsymbol{R} = (^{131}\mathrm{Xe}_r, {}^{132}\mathrm{Xe}_r, {}^{134}\mathrm{Xe}_r, {}^{136}\mathrm{Xe}_r)$ is the special fission plus *r*-process vector. We extend that point of view in this paper, explicitly distinguishing fission from the remainder of the *r*-process by the vector $F = (^{131}\mathrm{Xe}_f, {}^{132}\mathrm{Xe}_f, {}^{134}\mathrm{Xe}_f, {}^{136}\mathrm{Xe}_f)$ so that $\boldsymbol{R}$ can then be restricted to signify direct *r*-process production. Then from primary nucleosynthesis one can produce xenon of the form

$$\mathrm{Xe} = \boldsymbol{P} + \boldsymbol{S} + \boldsymbol{R} + \boldsymbol{F}\,. \tag{1}$$

The vector $\boldsymbol{S} = (^{128}\mathrm{Xe}_s, {}^{129}\mathrm{Xe}_s, {}^{130}\mathrm{Xe}_s, {}^{131}\mathrm{Xe}_s, {}^{132}\mathrm{Xe}_s)$ describes nucleosynthesis by the *s*-process (Clayton *et al.* 1961; see also Clayton 1968) and is the specific concern of the present paper. Before concentrating on that subject, however, we note for clarification that $\boldsymbol{R}$ contains also $^{129}Xe_r$ whenever $^{129}I_r$ has decayed, and that the size of the resulting anomaly depends upon whether the decay occurs in interstellar gas or in interstellar grains or in the meteorites (Clayton 1975). That is, $\boldsymbol{R}$ contains a special enhancement at ^{129}Xe dependent upon chemical fractionation of I from Xe before ^{129}I decay. Similarly, $\boldsymbol{F}$ might contain many types of fission, ranging from prompt fission at the termination of the *r*-process itself, and from the fission of special parents, such as ^{244}Pu or a superheavy, which may have been incorporated before fission into interstellar grains (Clayton 1975) or into the meteorites. Similarly, $\boldsymbol{R}$ may contain more than a single type of *r*-process (Black 1975; Clayton 1975). Furthermore, each of these vectors may have been modified by mass-dependent fractionation.

The possibility that $\boldsymbol{X}$ might represent variations in the strength of $\boldsymbol{S}$ occurred to Clayton (1975) as an explanation for the linear correlation between $^{124}Xe/^{132}Xe$ and $^{136}Xe/^{132}Xe$. This comes about because $^{132}Xe_s$ is the largest component of $\boldsymbol{S}$, so that variations of $\boldsymbol{S}$ with constant ^{124}Xe and ^{136}Xe would result in the linear relation. The scenario he proposed also was sympathetic to this possibility, since the supernova explosion synthesizes $\boldsymbol{P}$, $\boldsymbol{R}$, and $\boldsymbol{F}$, whereas $\boldsymbol{S}$ might be absent. On the other hand, grains forming in ejecta from atmospheres of giant stars might be much enriched in $\boldsymbol{S}$ and carry that anomaly with them. In this way $\boldsymbol{S}$ is fractionated from the other isotopes by residing partially in different carriers. In order that questions of this type might be addressed more easily, we present a discussion of $\boldsymbol{S}$ in this paper.

In Figure 1 we show the sequence of (n, γ) reactions defining the *s*-process path through the isotopes of Te, I, and Xe. The weak decays are shown as dashed lines. In evaluating the *s*-process yields, we will allow for competition between weak decays and neutron capture, following the analysis of Ward, Newman, and Clayton (1976) in defining the branching ratio for negatron decay to be $f_- = \lambda_-(\lambda_- + \lambda_+ + \lambda_{ec} + \lambda_n)^{-1}$ for each nucleus. The branches of interest for this problem are the competition between λ_- and λ_{ec} at ^{128}I and the competition between λ_- and λ_n at ^{129}I. Both weak decays are modified by the high electron density and temperature of the *s*-process site. Ward *et al.* found in their study of the *s*-process with branching that $T = 3.1 \times 10^8$ K seems to characterize most of the branches, and that a density $\rho = 2000$ g cm^{-3} probably represents the helium-burning shell where most of the *s*-process occurs. They also calculated an average neutron-capture time of 13 years for ^{129}I. We will adopt these as the most likely values for anomalous *s*-xenon in grains (evidenced either by its presence or by its absence).

Solar-system material contains a superposition of *s*-nuclei resulting from differing exposures of iron-group seed nuclei. Grains forming in specific stellar ejecta, on the other hand, might have an excess or a deficiency in a particular range of irradiations. Following Clayton *et al.* (1961; also Clayton 1968), the irradiations of iron seed are designated by τ and numerically expressed in units of 10^{27} n cm^{-2}. Then the product of (n, γ) cross section times *s*-process abundance can be adequately evaluated from

$$\psi_k(\tau) \equiv \sigma_k N_k(\tau) \approx \lambda_k \frac{(\lambda_k \tau)^{m_k - 1}}{\Gamma(m_k)} \exp(-\lambda_k \tau) \qquad (2)$$

where $k = A - 55$, and the parameters λ_k and m_k are generated by

$$m_k = \left[\left(\sum_{i=1}^{k} \frac{1}{\sigma_i}\right)^2\right] \Big/ \left[\sum_{i=1}^{k} \left(\frac{1}{\sigma_i}\right)^2\right], \quad \lambda_k = \left(\sum_{i=1}^{k} \frac{1}{\sigma_i}\right) \Big/ \left[\sum_{i=1}^{k} \left(\frac{1}{\sigma_i}\right)^2\right]. \qquad (3)$$

The cross sections for the xenon isotopes have not been measured, so we resort here to three different semiempirical

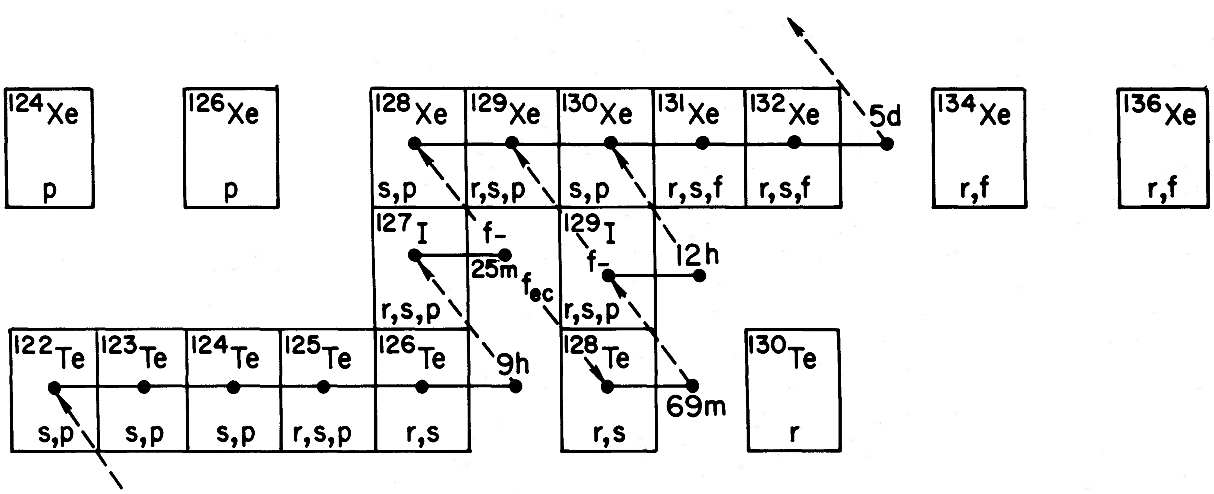

FIG. 1.—The *s*-process neutron-capture chain through Te, I, and Xe is shown by solid line connecting the points. The dashed lines indicate weak decays; for example, $f_-(^{128}I)$ is the fraction of 25m ^{128}I that undergoes negatron emission during the *s*-process. The dominant contributing processes to nucleosynthesis of each isotope are designated by *p*, *s*, *r*, *f* in order of yield.

TABLE 1

XENON DECOMPOSITION*

Quantity	Source	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe
σ(mb)............	HWFZ	232	666	143	587	90.9
	AGM	300	760	100	250	36
	BDRV	239	572	189	491	116
m_k...............	HWFZ	10.6186	10.6279	10.6689	10.6794	10.7408
	AGM	10.6129	10.6211	10.6776	10.7018	10.8245
λ_k...............	HWFZ	17.8314	17.8631	18.0065	18.0426	18.2643
	AGM	17.8116	17.8393	18.0409	18.1246	18.6332
ψ_k (τ = 1)†.......	HWFZ	0.2202	0.2182	0.2090	0.2068	0.1932
	AGM	0.2214	0.2197	0.2067	0.2017	0.1699
ψ_k (τ = 2)†.......	HWFZ	0.6280	0.6301	0.6401	0.6426	0.6583
	AGM	0.6266	0.6285	0.6427	0.6485	0.6875
N_s‡.............	HWFZ	60	22	≡100	24	150
	AGM	33	14	≡100	39	250
	BDRV	79	33	≡100	39	160
	HWFZ	0.13	0.048	≡0.22	0.053	0.33
N...............	Cam	0.117	1.48	0.229	1.15	1.40
N_r...............	N–N_s	≡0	1.43	≡0	1.10	1.07
δ_s...............	N_s/N	0.95	0.032	0.97	0.046	0.24

* The two p-isotopes (124 and 126) and the two r-isotopes (134 and 136) have not been included, since they have no s-component. Small p-process correlations of 0.006 have been subtracted from N(128) and N(130), and for the calculation of δ_s the remainder is assumed to exactly equal N_s.

† Calculated in this case with $f_-(^{128}\mathrm{I}) = 1$.

‡ Calculated for exponential $\rho(\tau)$ with $\tau_0 = 0.25$ with $f_-(^{128}\mathrm{I}) = 0.94$ and $f_-(^{129}\mathrm{I}) = 0.96$ (Ward *et al.* 1976).

estimates of their values. These are the first entries in Table 1. The cross sections σ(AGM) are the semiempirical estimates made by Allen, Gibbons, and Macklin (1971, hereafter AGM) in their review of neutron-capture cross sections for the s-process; those designated BDRV are from experimentally renormalized calculations of Benzi *et al.* (1973); alternatively, HWFZ are the values calculated without empirical corrections by Holmes *et al.* (1976) from a systematic theory of nuclear reactions. One sees considerable differences between the AGM set of cross sections and the other two, indicating a measure of the degree of uncertainty that will exist until the measurements are made. We actually expect the set σ(HWFZ) to be closer to the truth, considering the elaborate care of their calculations and the good agreement both with other cross sections that have been measured and with the set σ(BDRV). The values of m_k and λ_k for the xenon isotopes are then calculated for two of those sets of cross sections from the value for ^{127}I, which just precedes the s-process in xenon and which is characterized by $m_{72} = 17.7421$ and $\lambda_{72} = 10.5926$ mb. The resulting values are the next entries of Table 1, and these can be used in equation (2). The next entries in Table 1 show the values of ψ_k at two representative values of τ. It is immediately clear that ψ_k changes only gradually through the xenon isotopes and that the value of ψ_k is but weakly sensitive to the choice of xenon cross sections. The simple approximation σN_s = constant would be adequate for $1 < \tau < 2$. The insensitivity to the choice of cross sections means that the product $\sigma_k N_k = \psi_k$ has more generality than the abundances themselves, which are derived by $N_k = \psi_k/\sigma_k$ and are clearly more sensitive to the correct values of the cross sections. It follows that the values of ψ_k calculated from λ_k could be used even with other estimates of the cross sections σ_k. It should be noted that the absolute values of N_k computed from ψ_k in this way are normalized to be yield per iron-seed nucleus.

Although Table 1 shows that the components of $\boldsymbol{S}$ are well correlated for $1 < \tau < 2$, there does exist a weak effect due to the changing slope of ψ_k through the xenon isotopes. As the irradiation τ increases, $^{132}\mathrm{Xe}_s/^{130}\mathrm{Xe}_s$ also increases whereas $^{128}\mathrm{Xe}_s/^{130}\mathrm{Xe}_s$ decreases. This modest effect reminds us that even with a specific set of cross sections, the isotopic composition of $\boldsymbol{S}$ can vary somewhat from one radiation environment to another. This effect is, however, too small to influence cosmochemical considerations at the present time.

These results for the s-process isotopes of Xe have ignored the small electron-capture branch at ^{128}I. Since it is no more than a few percent, it produces no more than a few percent reduction in $^{128}\mathrm{Xe}_s/^{130}\mathrm{Xe}_s$ at each value of τ. With high accuracy the correct value of $^{128}\mathrm{Xe}_s/^{130}\mathrm{Xe}_s$ can be obtained by multiplying $\psi(^{128}\mathrm{Xe})$ by $f_-(^{128}\mathrm{I})$. This correction is smaller than the anticipated uncertainty in future measurements of the corresponding neutron-capture cross sections, and can therefore be ignored unless $f_{\mathrm{ec}}(^{128}\mathrm{I})$ can be greater than its laboratory value of 0.06. In the following calculations, however, we take into account both this branch and the one at ^{129}I because they can be explicitly included and because they do control the yields of $^{129}\mathrm{I}_s$ and $^{128}\mathrm{Te}_s$, which are also of potential interest.

It seems likely that $\boldsymbol{S}$ is actually characterized by a continuous distribution of irradiations. Seeger, Fowler, and Clayton (1965) showed that the solar-system s-process abundances resembled those resulting from an exponential distribution of irradiations of iron-group seed nuclei. In particular, $\rho(\tau)d\tau = Ge^{-\tau/\tau_0}d\tau$ was selected by them as the number of iron seed per 10^6 Si atoms that had received irradiation τ in the interval $d\tau$. In stellar atmospheres, the distribution appears (Danziger 1966) to remain exponential but to be characterized by differing values of τ_0 (whose value is about $0.25 \times 10^{27}\, n\, \mathrm{cm}^{-2}$ for the solar-system abundances, depending upon the cross sections adopted for the chain). It therefore seems sensible to discuss $\boldsymbol{S}$ in terms of the exponential distribution. With the results of Ward *et al.*, these ratios can be written explicitly with full dependence upon the cross sections, upon τ_0, and upon the branches at ^{128}I and ^{129}I. The effect of these branches on $\boldsymbol{S}$ is small because $f_{\mathrm{ec}}(^{128}\mathrm{I})$ is so small. However, the small branch $f_{\mathrm{ec}}(^{128}\mathrm{I})$ is nonetheless interesting in that it results in some production of ^{129}I and ^{128}Te by the *s*-process. We will take $f_{\mathrm{ec}}(^{128}\mathrm{I})$ to have its laboratory value of 0.06, although it may be even smaller in the *s*-process itself due to the fact that excited-state decay speeds λ_- more than continuum capture can speed λ_{ec}. A detailed calculation would be required for each environment; we will use $f_{\mathrm{ec}} = 0.06$ as both an estimate and a probable upper limit to this branch. Then the ratios of σN_s products can be written exactly in terms of the quantity

$$\zeta(^{A}Z) \equiv \left(1 + \frac{1}{\tau_0 \sigma(^{A}Z)}\right)^{-1} . \tag{4}$$

The relevant ratios of products of $\sigma(n, \gamma)$ and the *s*-process abundance N_s can be found recursively from the following relations:

$$\frac{\sigma(^{128}\mathrm{Xe})N_s(^{128}\mathrm{Xe})}{\sigma(^{127}\mathrm{I})N_s(^{127}\mathrm{I})} = f_-(^{128}\mathrm{I})\zeta(^{128}\mathrm{Xe}) , \tag{5}$$

$$\frac{\sigma(^{129}\mathrm{Xe})N_s(^{129}\mathrm{Xe})}{\sigma(^{128}\mathrm{Xe})N_s(^{128}\mathrm{Xe})} = \zeta(^{129}\mathrm{Xe})\left[1 + \frac{f_-(^{129}\mathrm{I})\sigma(^{129}\mathrm{I})N_s(^{129}\mathrm{I})}{[1 - f_-(^{129}\mathrm{I})]\sigma(^{128}\mathrm{Xe})N_s(^{128}\mathrm{Xe})}\right] , \tag{6}$$

$$\frac{\sigma(^{129}\mathrm{I})N_s(^{129}\mathrm{I})}{\sigma(^{128}\mathrm{Xe})N_s(^{128}\mathrm{Xe})} = \left[\frac{1}{1 - f_-(^{129}\mathrm{I})} + \frac{1}{\tau_0\sigma(^{129}\mathrm{I})}\right]^{-1} \frac{1 - f_-(^{128}\mathrm{I})}{f_-(^{128}\mathrm{I})} \frac{\zeta(^{128}\mathrm{Te})}{\zeta(^{128}\mathrm{Xe})} , \tag{7}$$

$$\frac{\sigma(^{130}\mathrm{Xe})N_s(^{130}\mathrm{Xe})}{\sigma(^{129}\mathrm{Xe})N_s(^{129}\mathrm{Xe})} = \zeta(^{130}\mathrm{Xe})\left[1 + \frac{\sigma(^{129}\mathrm{I})N_s(^{129}\mathrm{I})}{\sigma(^{129}\mathrm{Xe})N_s(^{129}\mathrm{Xe})}\right] , \tag{8}$$

$$\frac{\sigma(^{131}\mathrm{Xe})N_s(^{131}\mathrm{Xe})}{\sigma(^{130}\mathrm{Xe})N_s(^{130}\mathrm{Xe})} = \zeta(^{131}\mathrm{Xe}) , \tag{9}$$

and

$$\frac{\sigma(^{132}\mathrm{Xe})N_s(^{132}\mathrm{Xe})}{\sigma(^{131}\mathrm{Xe})N_s(^{131}\mathrm{Xe})} = \zeta(^{132}\mathrm{Xe}) . \tag{10}$$

We display these because they are exact solutions (for a steady *s*-process) to an important problem. For actual cosmochemical applications with the values of f_- chosen below, it would be adequate to use the much simpler σN_s = constant through Xe, considering that the cross sections are not accurately known.

In preparing Table 1 we have used these relations and normalized all of the calculated *s*-process abundances to $^{130}\mathrm{Xe} = 100$ for the three different sets of xenon cross sections discussed earlier. Note that these relative abundances are independent of all details of the capture path prior to ^{128}I. We actually performed calculations for three values of the exponential exposure parameter τ_0; however, only the results for $\tau_0 = 0.25$ are listed in Table 1 because the ratios for $\tau_0 = 0.15$ and $\tau_0 = 0.5$ were not significantly different for cosmochemical discussions. The value $\tau_0 = 0.25$ reproduces quite well the $A > 70$ portion of the solar-system σN_s curve; the values $\tau_0 = 0.50$ and $\tau_0 = 0.15$ would (all other quantities being equal) yield an enhancement factor of 15 and a depletion factor of 25, respectively, for $^{130}\mathrm{Xe}/^{56}\mathrm{Fe}$ relative to their solar-system ratio. In all cases we have also used $f_-(^{128}\mathrm{I}) = 0.94$ (laboratory value) and $f_-(^{129}\mathrm{I}) = 0.96$. The latter value comes from the average *s*-process environment found by Ward *et al.* and could be *considerably* altered by a different average neutron-capture time. The importance of the value of $f_-(^{129}\mathrm{I})$ lies not so much with xenon as it does with the amount of ^{129}I due to the *s*-process, as expressed in equation (7).

In calculating the absolute *s*-process solar-system xenon abundances, one can scale the equations given above back along the (unique) capture path to *s*-only ^{124}Te via

$$\sigma(^{127}\mathrm{I})N_s(^{127}\mathrm{I}) = \zeta(^{127}\mathrm{I})\zeta(^{126}\mathrm{Te})\zeta(^{125}\mathrm{Te})\sigma(^{124}\mathrm{Te})N_s(^{124}\mathrm{Te}) . \tag{11}$$

The ^{124}Te cross section has been well measured as 150 ± 20 mb (AGM) and using Cameron's (1973*a*) abundances (with a suitable small *p*-process correction) yields the experimental value $\sigma(^{124}\mathrm{Te})N_s(^{124}\mathrm{Te}) = 43.5$ mb per 10^6 Si atoms. With the set σ(AGM) this value propagates to $\sigma N_s = 40.3$ at ^{128}Xe, which is marginally higher than the value $\sigma N_s = 300\,(0.117) = 35.1$ using Cameron's (1973*a*) ^{128}Xe abundance, designated Cam in Table 1. Considering that the $\sigma(^{128}\mathrm{Xe})$ is not known, this seems reasonably good agreement. Even if Cameron's abundance ratio Xe/Te is somewhat incorrect, the decomposition of Xe isotopes is unaffected, since they are normalized at ^{130}Xe in Table 1. Thus uncertainties in the global σN_s curve have little effect on the needed Xe decomposition.

The abundances listed in Table 1 constitute our best estimates of $\boldsymbol{S}$ in the solar system. The largest uncertainty lies in the fact that the cross sections are not yet measured. The differences between the three sets of cross sections

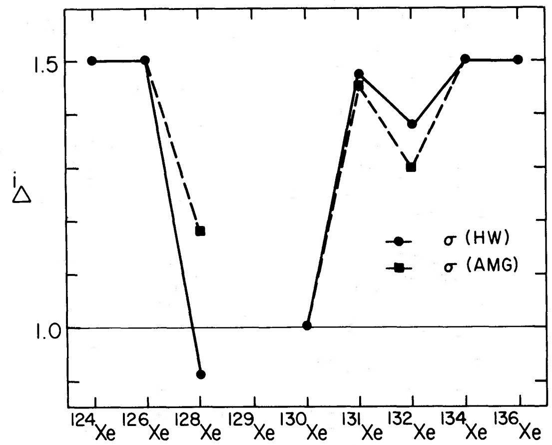

FIG. 2.—The enhancement factor ${}^i\Delta = ({}^i\mathrm{Xe}/{}^{130}\mathrm{Xe})({}^i\mathrm{Xe}/{}^{130}\mathrm{Xe})_\odot^{-1}$ obtained by subtracting S from solar xenon. The amount subtracted was arbitrarily chosen to be such that the enhancement of non-s-nuclei was equal to 1.5. Circles and squares distinguish between two sets of cross sections listed in Table 1. Of possible astrophysical interest is the similarity between this pattern and that of CCF Xe–X, as displayed in Fig. 5 of Lewis *et al.*

are self-evident, and equations (4)–(10) will make possible the calculation of S for any set of cross sections. Absolute values of N_s for σ(HWFZ) are tabulated after normalizing to N_s (^{130}Xe) = 0.22 per 10^6 Si. In spite of uncertainty concerning the correct cross sections, one sees that S is a major part of solar-system xenon only at A = 128, 130, and 132. If some solar-system sample had formed carrying an excess of N_s relative to the mixture in normal xenon, the isotopic fractional excesses $\delta_s = N_s/N$ would be numerically similar to the last row. It was obtained by demanding $N_r(128) = N_r(130) = 0$ and taking the natural abundances of those isotopes to be N_s. The small disagreement between N and calculated N_s at ^{128}Xe is attributed to inexact cross sections. The resulting distribution in N_s then looks plausible, since the N = 50 r-peak centers on ^{130}Te = 2.21. The dropoff through the untabulated ${}^{134}\mathrm{Xe}_r$ = 0.55 and ${}^{136}\mathrm{Xe}_r$ = 0.45 seems satisfactory.

With these results we can quantitatively see what solar xenon would look like if part of S were missing. In this way we can evaluate Clayton's (1975) observation that a deficiency in S would naturally lead to certain features of X (Manuel *et al.*; Clayton 1976). To do so, we subtract S from Xe and then renormalize to ^{130}Xe = 1. We take Xe from Cameron (1973*a*), but average carbonaceous-chondrite xenon would clearly give the same result. Specifically, we calculate the enhancement factor

$$
\begin{aligned}
{}^i\Delta &= ({}^i\mathrm{Xe}/{}^{130}\mathrm{Xe})_{\mathrm{sample}}({}^i\mathrm{Xe}/{}^{130}\mathrm{Xe})_\odot^{-1} \\
&= \frac{C\,{}^i\mathrm{Xe}_\odot - {}^i\mathrm{Xe}_s}{C\,{}^{130}\mathrm{Xe}_\odot - {}^{130}\mathrm{Xe}_s}\left(\frac{{}^i\mathrm{Xe}}{{}^{130}\mathrm{Xe}}\right)_\odot^{-1} . \qquad (12)
\end{aligned}
$$

The results are plotted in Figure 2, where C is a normalizing constant chosen so the correlated overabundances at A = 124, 126, 134, 136 have arbitrarily the value of 1.5. The value 1.5 was chosen for convenience in comparing with published displays of anomalous xenon (e.g., Lewis, Srinivasan, and Anders 1976). With this choice we also have

$$
\Delta = 1.5 - 0.5\left(\frac{{}^i\mathrm{Xe}}{{}^{130}\mathrm{Xe}}\right)_s\left(\frac{{}^i\mathrm{Xe}}{{}^{130}\mathrm{Xe}}\right)_\odot^{-1} . \qquad (13)
$$

The results are plotted for two sets of cross sections with τ_0 = 0.25. It is clear that the shape is not the same as that given by Lewis *et al.* in their Figure 5, confirming the tentative conclusions of Clayton (1975) that this type of renormalization is not involved with X. On the other hand, two features bear strong similarity to X: (1) the enhancements at ^{124,126}Xe and ^{134,136}Xe are correlated and about equal in magnitude; and (2) there is a dip at ^{132}Xe between ^{131}Xe and ^{134}Xe. It is the very large overabundance of ^{131}Xe in this renormalization that apparently dooms Clayton's conjecture, as he thought. On the other hand, it may be that an effect like this one combines somehow with other effects (fractionation and other nuclear components) to play a role in X. That is the main justification for the detailed treatment we have presented here. We will not speculate on such other effect here, but restrict our discussion to S itself.

The behavior of ^{128}Xe/^{130}Xe in Figure 2 is also interesting. If both isotopes were exclusively due to the s-process and if the correct cross sections were used, then ${}^{128}\Delta$ would also be unity just as ${}^{130}\Delta$ is. In Figure 2 the value of

$^{128}\Delta$ moves because the correct cross sections are unknown. It is of potential importance that $^{128}\Delta$ may in fact exceed unity, in which case the *p*-process contribution to ^{128}Xe is a greater fraction of its abundance than $^{130}Xe_p$ is of ^{130}Xe. Clayton (1976) emphasized the importance of understanding ***P*** for the entire xenon problem, and he pointed out that careful measurements of $\sigma(^{128}\mathrm{Xe})/\sigma(^{130}\mathrm{Xe})$ would be a valuable aid to that understanding.

A deficiency in ***S*** is equivalent to an excess in ***R*** + ***F*** insofar as the isotopes $128 \leq A \leq 136$ are concerned. Figure 2 therefore displays equally well the fact that Xe–*X* cannot be an enhancement of the average unshielded isotopes. This realization led to suggestions that Xe–*X* represents either fission (Lewis *et al.*), a special component of the *r*-process (Black 1975; Clayton 1975), or an injection from a neighboring supernova (Manuel *et al.*; Cameron and Truran 1977). Curiously, for a similar situation in Nd, Clayton (1978) has shown that the data suggest an excess of the *average r*-isotopes, probably resulting from their physical fractionation from the *s*-isotopes in the interstellar medium. Careful measurements of the Nd cross sections are called for in that case to substantiate this remarkable conclusion. For the present Xe case, however, it is clear that the calculated cross sections σ(HWFZ) cannot be sufficiently wrong that Xe–*X* could yet prove to be merely an enhancement of average ***R*** + ***F***. There thus exist puzzling differences between the Xe and Nd discoveries, and it is our hope that the detailed decompositions we have given can ultimately shed light on this important cosmological problem.

a) ^{129}I

It is of some interest to note that some ^{129}I is made by the *s*-process. We estimate that the average *s*-process nucleosynthesis has resulted in $(^{129}\mathrm{I}/^{130}\mathrm{Xe})_s \approx 7 \times 10^{-4}$. This value is four orders of magnitude less than the solar ratio $(^{129}\mathrm{Xe}/^{130}\mathrm{Xe})_\odot = 6.5$, which suggests that the *s*-process has probably not made more than 10^{-4} of total ^{129}I. However, if the *s*-process conditions turn out to yield values of $f_-(^{128}\mathrm{I})$ and $f_-(^{129}\mathrm{I})$ that are less than 0.9, instead of greater than, as we have assumed, the yield of $^{129}I_s$ could easily be one to two orders of magnitude greater. The question would be of interest if grains form in envelopes ejected from red giants that are enriched in *s*-elements, since they would later contain special ^{129}Xe (Clayton 1975).

b) *s-r-Fractionation*

We also wish to comment on one general aspect of the cosmochemistry of interstellar grains. If these grains do form in stellar ejecta as we speculate, they will have substantial fractionations of ***S*** and ***R*** along the lines of the xenon example of this paper. We need more searches for small correlated variations of ***S*** (or ***R***) in elements having isotopes due to both processes. It is of interest that Cameron (1973*b*) has already suggested this, but for quite a different reason. He speculated that there might be incomplete mixing *in the interstellar gas* between *s*- and *r*-process elements, whereas we put the finger on the grain component that forms in individual stars. Fluctuations between dust and gas and different types of dust during cold accumulation processes in the solar nebula are envisioned as resulting in planetesimals liberating differing internal xenon and krypton atmospheres. The carriers of these gases today were formed in these protoplanetesimals, trapping the anomalous atmosphere, and then dispersed for later incorporation into meteorites. One should expect to have to study very small meteoritic samples before finding the differences, however, since they may be lost in an ensemble of a large number of presolar grains.

III. KRYPTON

Anomalous Kr was found by Lewis *et al.* and subsequent workers (e.g., Frick 1977) to accompany Xe–*X*. It therefore seems desirable to provide a decomposition of Kr similar to that provided in Table 1 for Xe. Unfortunately, this cannot be convincingly done at the present time, at least for all of the key isotopes.

The ratio of *s*-only nuclei, ^{80}Kr and ^{82}Kr, depends on the branching at ^{79}Se. Ward *et al.* have discussed in detail how this can be used to obtain thermodynamic information on the average *s*-process, but the ratio will be quite variable in different *s*-process environments. Nonetheless, to analyze the possibility that N_s is fractionated from N_r in the interstellar medium owing to their differential incorporation into different types of stardust, ^{80}Kr and ^{82}Kr should be thought of as having resulted almost entirely from the *s*-process. Something like 70% ± 15% of ^{84}Kr should also be N_s, but the cross sections are not known with anywhere near enough accuracy to be more precise. For ^{83}Kr, on the other hand, the *s*-process fraction is rather clearly in the 20%–30% range; i.e., largely *r*-process.

The largest problem is ^{86}Kr. It is an old controversy (Seeger *et al.*) whether this is an *r*-process product or largely an *s*-product. The problem hinges on the branching of ^{85}Kr decay in the average *s*-process. Ward *et al.* discussed this in detail and concluded $f_-(^{85}\mathrm{Kr}) = 0.82$, leading to $N_s(^{85}\mathrm{Kr}) = 5$ with AGM cross sections, see their equation (63). The value of $\sigma(^{86}\mathrm{Kr})$ is too poorly known to give one much confidence in this result, however. It may reasonably happen that anywhere from 0% to 90% of ^{86}Kr is the result of the *s*-process, depending on the β-branch $f_-(^{85}\mathrm{Kr})$. As a result, we cannot with confidence predict the behavior of this key experimental nucleus in an *s*-process enhancement of deficit.

In summary, an *s*-enhancement of Kr would enhance ^{80}Kr, ^{82}Kr, and ^{84}Kr by large fractions, leaving ^{78}Kr and ^{83}Kr underabundant (almost absent). Krypton-86 is probably intermediate, since $N_r \approx 4$ looks plausible from the general *r*-process yield curve. This decomposition, uncertain as it is, is displayed for two sets of cross sections in Table 2. A value $N_p = 0.166$ is assumed for each isotope except ^{84}Kr and ^{86}Kr. The AGM cross sections used by

TABLE 2
KRYPTON DECOMPOSITION

Quantity	Source	^{78}Kr	^{80}Kr	^{82}Kr	^{83}Kr	^{84}Kr	^{86}Kr
σ(mb)............	HWFZ	203	148	122	571	25	4.36
	AGM	250	140	80	225	28	9
N_s*.............	HWFZ	0	0.90	5.25	1.13	22.0	$64[1-f_-(85)]$
	AGM	0	0.90	5.25	1.87	13.1	$28[1-f_-(85)]$
N..............	Cam	0.166	1.06	5.41	5.41	26.6	8.13
N_r†............	HWFZ	0	0	0	4.12	4.6	?
	AGM	0	0	0	3.38	13.5	?
$N_s/N = \delta_s$........	...	0	0.85	0.97	0.21	0.83	?
	...	0	0.85	0.97	0.34	0.49	?

* Calculated with exponential $\rho(\tau)$ with $\tau_0 = 0.25$.
† $N_p = 0.16$ assumed for $A = 78$, 80, 82, and 83.

Ward *et al.* are suspect in the smallness of the ratio $\sigma(^{82}\mathrm{Kr})/\sigma(^{84}\mathrm{Kr})$, which results in $N_r(^{84}\mathrm{Kr}) = 13.5$. This value seems too large in comparison to the N_r for both ^{83}Kr and ^{85}Rb. The small $\sigma(^{86}\mathrm{Kr})$ in HWFZ, on the other hand, demands that $f_-(^{85}\mathrm{Kr}) > 0.88$, whereas 0.82 works well with the AGM cross sections. Until these cross sections are accurately measured, Kr cannot be decomposed with the confidence applicable to Xe. The exact value of $f_-(^{85}\mathrm{Kr})$ will perhaps not be easily determinable to the accuracy needed to calculate $N_s(^{86}\mathrm{Kr})$.

IV. CONCLUSION

Unquestionably the correlated Xe and Kr anomalies in carbonaceous chondrites hold major clues to the origin of the solar system. Yet they have defied explanation. If our view proves correct, they will be complicated nucleosynthetic mixtures carried differentially in presolar grains, perhaps transferred to the present meteoritic carriers in protoplanetesimal internal atmospheres, in which case the anomalies help indicate both nucleosynthesis and the accumulation processes. The widespread interest in them prompts us to discuss the decomposition into *s*- and *r*-abundances. Xe–*X* may yet prove to be a deficiency of ***S***, although it must be complicated by fractionation and admixture with other small nuclear effects. Cross-section measurements are needed, especially for Kr. One also hopes to somewhere find the complementary excess in ***S***. Its existence is a prediction of the model used here, and failure to find it anywhere would favor other interpretations based on injection of a special Xe–*X* component (Manuel *et al.*). Gas-dust fractionation is expected to result in some level of *s*-*r*-fractionation in all heavy elements, because the fraction condensed in interstellar dust should not be independent of the type of stellar origin.

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DONALD D. CLAYTON: Department of Space Physics and Astronomy, Rice University, Houston, TX 77001
RICHARD A. WARD: Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125