for his interest in and assistance with this problem.

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DETERMINATION OF THE AGE OF THE ELEMENTS*

J. H. Reynolds
Miller Institute for Basic Research in Science and Department of Physics,
University of California, Berkeley, California
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We have found that xenon from the chondritic (stone) meteorite Richardton is heavily enriched in Xe^{129}. This isotope almost certainly was formed from the radioactive decay of I^{129}, now extinct as a natural radioactivity but not so at the time of formation of the meteorite. From the data we calculate that $(0.35 \pm 0.06) \times 10^9$ years elapsed between the time of formation of the elements and the meteorite. There is a large body of evidence that the chondrites were formed at a time close to 4.6×10^9 years ago. Thus the age of the elements is close to 4.95×10^9 years.

In 1947, Brown[1] suggested that the meteorites could be used to determine quite accurately the age of the elements if the daughter of an extinct natural radioactivity could be found there. The decay

$$I^{129} \xrightarrow{1.7 \times 10^7 \text{ yr}} Xe^{129}$$

has long been recognized as a particularly favorable case for stone meteorites, although previous searches for fossil Xe^{129} in the chondrite Beardsley[2] and the achondrite Nuevo Laredo[3] failed to give a positive result.

Figure 1 is a faithful tracing of the peak heights recorded with a sensitive mass spectrometer[4] during one of the sweeps of the spectrum of xenon which had been extracted from the vacuum melting of a 7-gram sample of Richardton. The horizontal lines drawn through the various peaks show where the peaks would fall for an analysis, under identical conditions, of a sample of atmospheric xenon[5] having the same Xe^{132} content. Differences between the two spectra, notably the large Xe^{129} excess in the meteoritic sample, are very obvious from the figure. A sequence of runs on four independently prepared xenon samples from this meteorite, interspersed with runs on atmospheric xenon, have established beyond any possible doubt

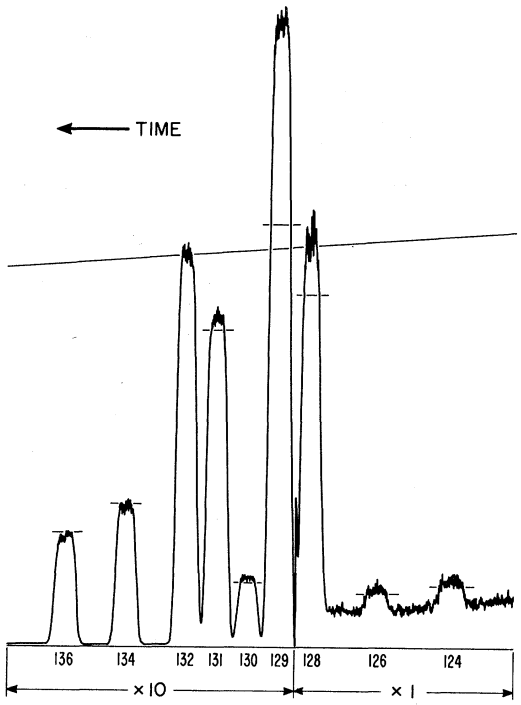

FIG. 1. Mass spectrum of Xe extracted from Richardton stone meteorite and sealed off in the mass spectrometer. Horizontal lines show the comparison spectrum of terrestrial Xe. The slant line through the 132 peak shows the extent of spectrometer pumping. Jagged peak tops are due to statistical fluctuations in the small ion currents.

that all of the differences seen in Fig. 1—including those at the rare masses 124 and 126—are real and are not due to such extraneous effects as chemical impurities, spectrometer "ghost" peaks, spectrometer memory from previous anomalous xenon samples (there had been none in this instrument), or instrumental instability. For example we have plotted in Fig. 2 both the meteoritic xenon spectrum and a spectrum from a sample of atmospheric xenon of the same size, the points normalized to the atmospheric abundances in both cases. In these two plots, mean deviations are indicated whenever they exceed the size of the points.

It will be noted in Fig. 2 that 136 is the least abundant isotope in the meteorite relative to atmospheric abundances. Accordingly, for the purposes of the calculations in this Letter, it has been assumed that the Xe^{136} in the sample of xenon from the meteorite is an index to the xenon of terrestrial composition in the sample, whether by contamination from the atmosphere or otherwise. The isotopic composition of the xenon from the meteorite, after this terrestrial component has been subtracted, appears in Table I. The errors quoted are mean deviations.

A Xe^{128} spike was used to determine the amounts of xenon in the meteorite. Care was taken not to introduce spiked samples into either the extraction apparatus or the mass spectrometer until all questions about the unspiked isotopic composition had been settled. Solid KI which had been outgassed in vacuum, finely powdered, and then briefly irradiated in a pile was the means by which the small amounts of tracer Xe^{128} required were handled. The results of the isotopic dilution analysis appear in Table I. One gram of Richardton contains 13×10^{-11} cc STP of excess Xe^{129}. This disagrees with the conclusions of Wasserburg and Hayden[2] who found an upper limit of 1.3×10^{-11} cc STP/g in the Beardsley meteorite.

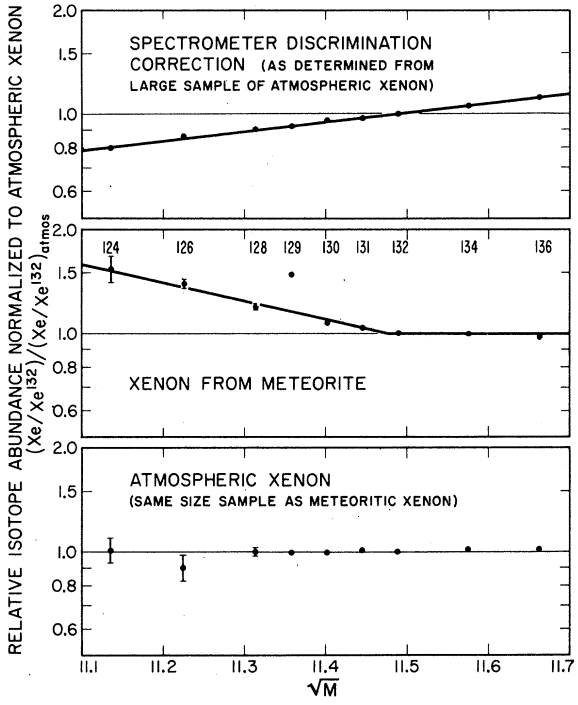

FIG. 2. Relative isotope abundance normalized to atmospheric xenon. $(Xe/Xe^{132})/(Xe/Xe^{132})_{atmos}$.

The presence of isotopes other than 129 in the anomalous spectrum probably means that other nuclear processes, induced by cosmic-ray bombardment, have contributed to the xenon in Richardton. This raises the question of whether the Xe^{129} might have been produced by some means other than the decay of extinct I^{129}. Quite aside from the difficulties involved in accounting for so much Xe^{129} production from the limited number of heavy-target nuclei available in the meteorite, strong arguments based on the isotopic composition of the anomalous xenon can be advanced against such mechanisms dominating the Xe^{129} production. Of particular importance

Table I. Xe from sample *KA* 382-2*H*: 6.69 g of Richardton, 20-100 mesh.

	Isotopic composition of anomalous component								
Isotope	124	126	128	129	130	131	132	134	136
Percent abundance	0.33±0.09	0.23±0.02	2.5±0.3	81.5±3.5	2.3±0.4	8.2±2.0	3.6±2.3	1.4±1.0	≡0

Xenon of terrestrial composition: $(0.88\pm0.05)\times10^{-9}$ cc STP/g

Xenon of anomalous composition: $(0.16\pm0.01)\times10^{-9}$ cc STP/g

in this connection is the fact that in the anomalous component, Xe^{129}/Xe^{131} is 10.0. Table II lists various possible mechanisms for Xe^{129} production with the Xe^{129}/Xe^{131} ratio expected in each case. None fit the observations. We are forced to conclude that I^{129} decay has produced the bulk of the Xe^{129}.

The time interval between nucleogenesis and the formation of the meteorite is given by

$$\Delta t = \frac{1.72\times 10^7}{0.693}\left[\ln(I^{127}/Xe^{129})_{met} + \ln(I^{129}/I^{127})_0\right] \text{ years.}$$

We assume that $(I^{129}/I^{127})_0 = 1$, i.e., that I^{129} and I^{127} were produced initally in equal amounts. Analytical data on I in chondrites are poor. Suess and Urey[6] adopt 0.66 ppm, but this could be wrong by a factor of 10 for any particular meteorite. We used 1 ppm in the calculation. This leads to $\ln(I^{127}/Xe^{129})_{met} = 14.1$ and $\Delta t = 0.35\times 10^9$ years. Fortunately, an error of a factor of 10 in either $(I^{127})_{met}$ or $(I^{129}/I^{127})_0$ leads to only a 16% error in Δt.

Now that the presence of radiogenic I^{129} in meteorites has been established, the I-Xe method of dating meteorites should assume importance. It has the unique advantage that it dates meteorites from the beginning of the solar system rather than from the present.

One curious feature of the isotopic composition of the anomalous xenon component should be mentioned. This is the fact that, excluding I^{129}, the abundances of the 5 lightest isotopes fit a smooth curve when normalized to the abundances of atmospheric xenon. In Fig. 2, these normalized abundances have been plotted logarithmically against $\sqrt{M}$ and give a straight line. (This is not an instrumental effect but is in addition to the rather strong mass discrimination of the spectrometer arising from the magnetically unshielded electron multiplier. This correction, also plotted in Fig. 2, has already been applied.) This raises the possibility that the anomalies at masses 124-131 may not be due to nuclear processes at all, but may be due to a strong mass fractionation of meteoritic xenon relative to terrestrial xenon—such as might occur if terrestrial xenon is the final residue of gas which has mostly escaped from a gravitational field at some time during its history. The heavy isotopes 132, 134, and 136 do not fit the pattern. It is conceivably significant that these are the chief isotopes produced in slow-particle and spontaneous fission. In fact, the meteoritic spectrum can be decomposed quite well into a "fractionated" terrestrial component (including masses 132, 134, and 136) plus a fission xenon spectrum. Of course, presence of atmospheric contamination in the meteoritic sample would alter the composition of the "fission" xenon deduced in this way.

Table II. Possible mechanisms for Xe^{129} production.

Mechanism	(Xe^{129}/Xe^{131})
Slow-particle or spontaneous fission	<1
Fast-particle fission	>1 but ~1[a]
Spallation reactions on Cs, Ba, or heavier elements	<1 but ~1
Natural neutron capture in Te	3[b]
Observed	10.0

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