The Time Scales of Nucleosynthesis

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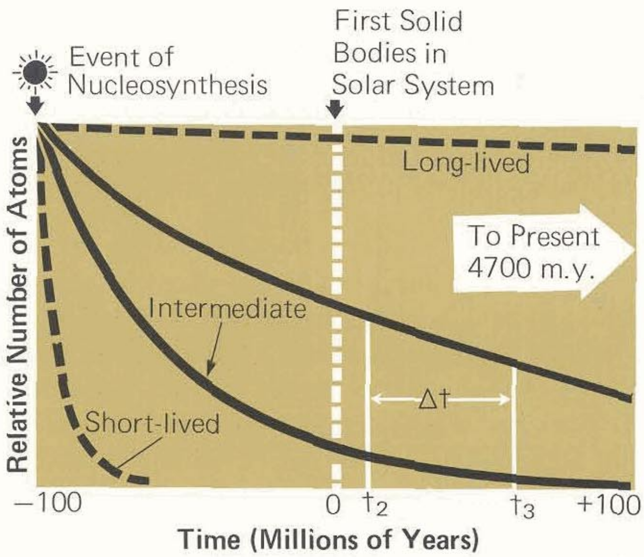
The nuclei of the atoms of elements heavier than hydrogen are generally believed to have been synthesized in a variety of stars, more or less continuously, throughout the history of the galaxy. The matter ejected from these stars at various stages in their evolution is mixed into the interstellar gas and, in turn, portions of this gas become isolated from the remainder of the galaxy and form later-generation stars such as the sun. The times required for the various stages in the evolution of the matter of our solar system are of interest, both from an astrophysical and a philosophical point of view. We will discuss how relatively definitive information can be obtained on the times for at least the latter stages in this evolution through the measurement of the isotopic composition of those elements in meteorites which contain the daughter products of radioactive decay.

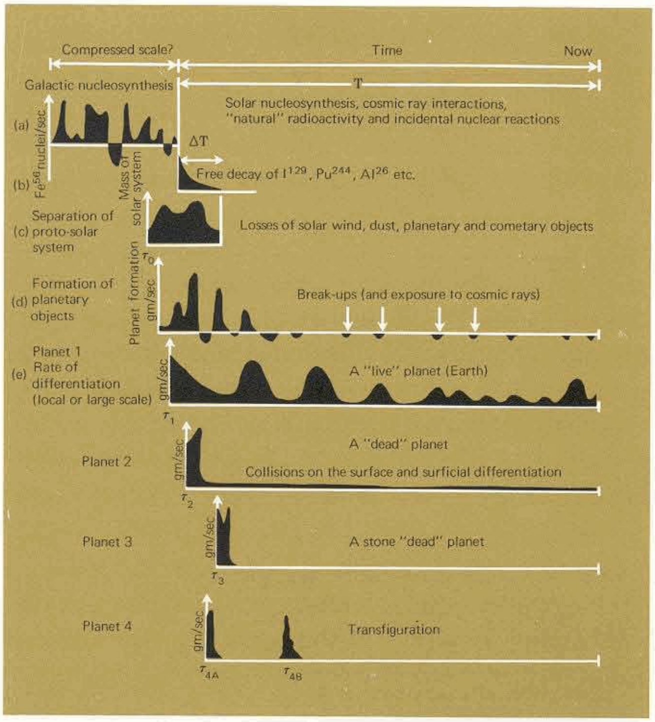
Information on the order of magnitude of the time that has elapsed since the matter in our solar system was "seriously" involved in nucleosynthetic activity is obtained from the simple observation of the presence or absence of certain radioactive species. All of the radioactive isotopes observed on the earth either have half-lives greater than about 10^9 years, or are the decay products of such elements. (Radioactive nuclei diminish in amount by a factor 2 in a time equal to the half-life of a nucleus.) This ignores the feeble level of nuclear reactions due to cosmic rays. Thus the matter which makes up our planet (also meteorites and the moon) has been removed from nucleosynthetic activity for times greater than 10^9 years. The absence of the shorter lived radioactivities is a consequence of the age of the solar system—about 4.7×10^9 years.

It is of considerable interest to seek evidence for the existence of element formation processes near the time of formation of the solar system. The diagram below illustrates the effect of a *hypothetical* event of nucleosynthesis occurring 100 million years before the formation of the first solid bodies in the solar system. Those nuclei which are short-lived (compared to 100 million years in this example) have completely decayed by the time solid objects are formed. For a half-life of 10 million years the exponential decay factor is 2^{-10}. Those "intermediate"



Addition of nuclei to the first solid bodies formed in the solar system from an event of nucleosynthesis at —100 million years. Simple exponential decay curves are shown for stable and radioactive nuclei with lifetimes long, intermediate, and short—compared to 100 million years.

nuclei whose lifetimes are comparable to the time interval between the event of nucleosynthesis and the formation of solid bodies will be incorporated into these bodies then, but will have completely decayed by the present time. Pu^{244} (82 million years half-life) is an example. The experimental upper limit for the ratio of Pu^{244} to U^{238} in modern terrestrial materials is about 10^{-14}, while it was almost certainly present in meteorites when they formed with $Pu/U \sim 1/30$. The hypothetical event shown on page 41 may be considered to be only one of a large number of galactic events which contributed matter to our solar system. This segment of the time scale should be considered



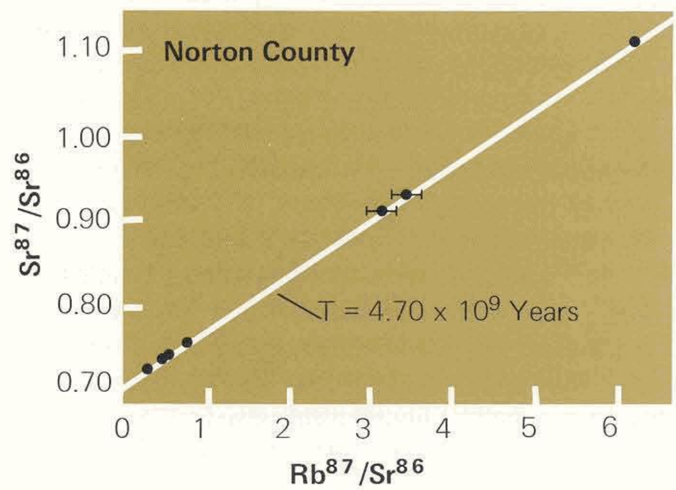
A generalized chronology for the solar system.

in the broader context of the generalized chronology for the solar system above. The period of nucleosynthetic activity is indicated in the topmost graph of the chart (a) which shows the rate of Fe^{56} production. This is terminated at the time marked by a vertical bar T years ago. Line b corresponds to the decay of intermediate-lived radioactive elements resulting from the superposition of individual events as shown on the diagram on page 41.

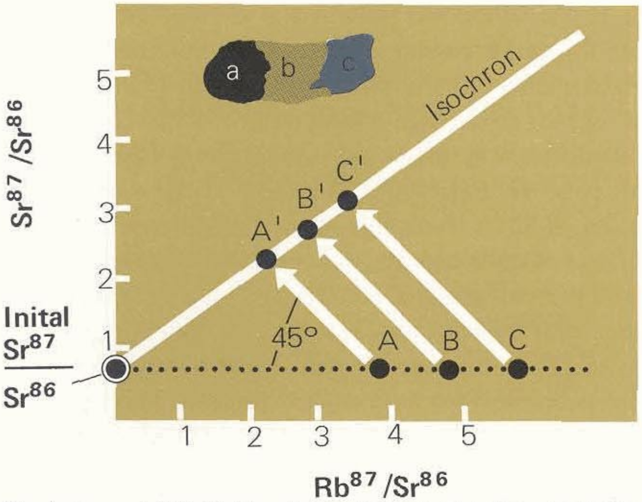
After the isolation and separation of nebular matter to form the solar system (c above), the sun and planetary objects start to condense. Subsequent to this, the solar system remains closed except for minor exchanges of matter with the remainder of the universe. All the planets probably formed during this early period. Subsequent to their initial formation, some of them (the asteroids) have been broken up by collision over the whole history of the solar system (d left). The small fragments are then exposed to cosmic ray bombardment. The effects of this bombardment allow us to calculate when these breakups took place. Four planetary bodies are shown forming at different times relative to the termination of nucleosynthesis. It is in fossil objects left over from these times that evidence of the intermediate-lived (10^7 to 10^9 years) nuclear products may be found which allow us to look back into presolar system processes.

The meteorites appear to be small fragments of such "planets" left over from the time of formation of the solar system. These planetary objects have undergone only a few changes since their formation, except to grow older and occasionally to be shattered into small pieces, some of which fall on the earth and other planets. They are thus fragments from "stone dead" planets (Planet 3, left). The dating of these objects either singly or in conjunction with the earth provides the basic time scale for the solar system. In contrast with the meteorites, the earth, which is a live planet, undergoes continuous rejuvenation both chemically and physically (Planet 1, left). Terrestrial material is constantly melted and recrystallized or weathered and is continuously mixed and transformed. Only the isotopic abundances reflect its original condition.

The ages of meteorites, as measured from the present, are obtained by the study of long-lived nuclei such as K^{40}, Rb^{87}, Th^{232}, U^{235} and U^{238}. The decay of



Sr^{87}/Sr^{86} evolution for the Norton County meteorite.



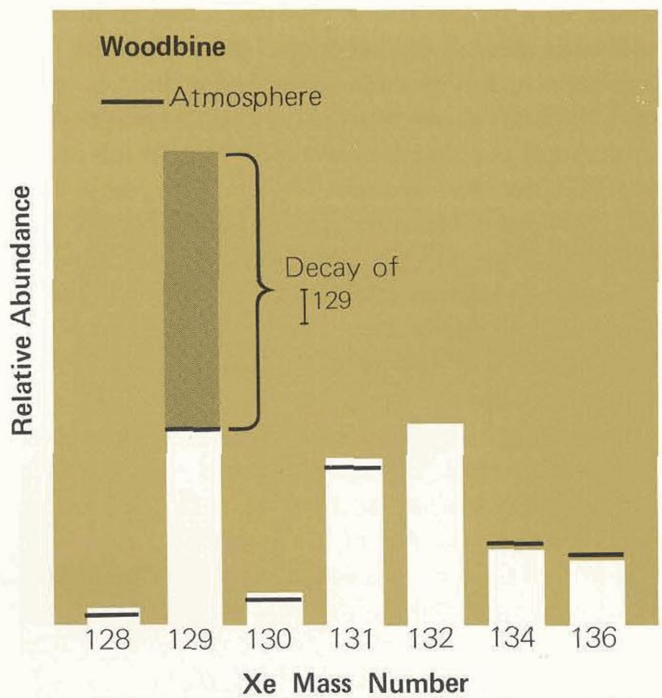
Evolution of Sr^{87}/Sr^{86} ratio in three parts of a meteorite.

Rb^{87} to Sr^{87} has proved to be particularly useful for this purpose. Generally speaking, Rb and Sr are inhomogeneously distributed in a meteorite, either due to the simple fact that a meteorite is a mixture of minerals of different chemical composition or, for more obscure reasons, due to variations in composition from one portion of the sample to another. Consider three parts of a meteorite (a, b, c, above) which formed with different ratios of Rb^{87}/Sr^{86}. However, the isotopic composition of the Sr (measured as Sr^{87}/Sr^{86}) will initially be the same in all three parts (points A, B, C). Sr^{86} is a stable isotope of Sr, and, barring chemical or thermal alteration, its concentration does not change with time. However, as time passes, the Sr^{87}/Sr^{86} ratio will increase as the result of the decay of Rb^{87} into Sr^{87} with larger increases occurring in those parts having a higher Rb^{87}/Sr^{86} ratio (above). Today, a plot of the measured Sr^{87}/Sr^{86} ratio vs. the measured Rb^{87}/Sr^{86} in each sample (A′, B′, C′) will give a straight line. The age can be calculated from the slope of this line, and the initial Sr^{87}/Sr^{86} ratio is given by the intercept. Such a plot for an actual meteorite (left) demonstrates that the simple evolutionary model (above) does, in fact, apply to many real situations, allowing accurate ages and initial Sr^{87}/Sr^{86} values to be obtained. Occasionally some meteorites are formed by a more recent (3.8×10^9 years) transfiguration (such as Planet 4 on page 42) and show us that other planets besides the earth have been subject to reformation since they were first made.

We can also obtain a more detailed view of the processes which took place at the termination of nucleosynthesis and planet formation. Those solid objects (planets, small fragments, grains) that formed during or immediately after nucleosynthesis will have the best chance of trapping the short- and intermediate-lived radioactive isotopes. The decay products of these radioactive isotopes, particularly when trapped in "stone dead" planetary objects, are a direct measure of the time ΔT between the formation of these objects and the termination of nucleosynthesis. Even more important, they tell us the time scale for the processes which produced the elements.

The simple existence of these intermediate-lived nuclei at the time of formation of most meteorites allows us to conclude with a high degree of certainty that the ages of these meteorites, as measured from the present, can be equated with the age of the solar system as a whole.

Evidence exists that I^{129} (17 m.y. half-life) and Pu^{244} (82 m.y. half-life) were present in meteorites when they formed. The presence of I^{129} (originally discovered by J. H. Reynolds of the University of California) in the early solar system is of great significance. At the present time, all of the I^{129} atoms



A portion of the mass spectrum of Xe from the Woodbine meteorite (linear scale). A comparison with atmospheric Xe, made by normalizing to mass 132, is shown by the dark lines. The dark area represents excess Xe^{129}, presumably from the decay of I^{129}. The small differences at mass numbers 128, 130, and 131 reflect primarily small deviations in the isotopic composition of primordial Xe in meteorites from that in the terrestrial atmosphere.

initially present in a meteorite will have been transformed into Xe^{129} by radioactive decay. Because Xe is a rare gas, most meteorites retain only about 5×10^9 "primordial" Xe atoms/gram when they form. Thus, because about the same number of I^{129} atoms were typically present, a pronounced Xe^{129} excess results in most meteorites compared either to the isotopic abundance of Xe^{129} in those unusual meteorites which contain large amounts of rare gases or to the Xe^{129} isotopic abundance in the earth's atmosphere (page 43). The initial existence of I^{129} in meteorites shows that they formed no later than about 100 million years after the last event of nucleosynthesis. However, other workers have shown that neither Pd^{107} (7 million years) nor Tc^{97} (3 million years) appear to have been initially present in meteorites. The experimental upper limits are relatively high; nevertheless, very large events of nucleosynthesis just prior to the formation of solid bodies can be ruled out.

Some heavy nuclei, such as U^{238}, occasionally decay by a relatively rare process known as spontaneous fission in which the U^{238} nucleus splits into two lighter nuclei (fission products). For example, Xe^{136} would be a typical fission product, although a wide variety of other fission products are also formed. The amount of energy given to the fission products is large (80-100 MeV); however, if the fission event occurs in a crystal, the distance travelled by the fission product is very small, only about 10^{-3} cm. This results in a large amount of radiation damage in the crystal along the path of the fission product. This damaged material is much more subject to chemical attack than the bulk material, and treatment with an appropriate etching agent produces a hole or "fission track" which marks the original fission event.

It has been demonstrated by Fleischer, Price, and Walker that many more fission tracks are present in crystals in meteorites than can be accounted for by U^{238} spontaneous fission. In conjunction with J. Huneke of Caltech, we have just shown that these same crystals contain a great excess of fission products (xenon). The isotopic spectrum of this fission Xe is different from that observed in any type of U fission. These results clearly show the existence of fissionable, transuranic elements during the beginning of the solar system, possibly Pu^{244}. From such observations we conclude that the solar system was not too removed in time from at least one of the "r" (rapid) type nucleosynthesis events in which neutrons were bountiful (a mole of neutrons per cc). (See article by William Fowler in this issue.)

In the future we plan to test the compatibility of the time information obtained from the intermediate-lived nuclei with that from the long-lived nuclei. Consider two meteorites whose parent bodies formed at two different times, t_2 and t_3 after $t = 0$ (the diagram on page 41 and Planets 2 and 3 on the diagram on page 42 left). Comparisons of the isotopic composition of many elements between meteorites and terrestrial samples make it very likely that all the matter in the solar system was isotopically homogeneous at $t = 0$. Thus, because isotopic fractionations in chemical processes are very small, the I^{129}/I^{127} ratio between two meteorites will differ only due to the decay of I^{129}, and comparison of the measured (excess Xe^{129})/I^{127} ratios allows the difference in formation times (Δt) to be calculated. No knowledge of the absolute I^{129}/I^{127} at $t = 0$ is required. Many meteorites were formed within two million years of each other, back at 4.6×10^9 years ago (as shown by Hohenberg, Podosek, and Reynolds at U. C. Berkeley).

In principle, Δt can also be obtained by precise measurement of time differences with respect to the present using Rb^{87} - Sr^{87}. The accurate measurement of slopes of lines (page 42 bottom) can only resolve time differences of about 50 to 100 million years with present techniques except in very favorable cases. However, qualitative information about small age differences in meteorites can be obtained if a precise *direct* measurement of the initial Sr^{87}/Sr^{86} (intercept in the diagram at the top of page 43) can be made on a part of the meteorite with a low Rb^{87}/Sr^{86} ratio (e.g., a Sr-rich mineral). D. Papanastassiou, in our laboratory, has found that the initial Sr^{87}/Sr^{86} in Rb-poor meteorites can be measured with a precision of $\pm$ 6 parts in 10^5.

To illustrate the significance of this result, suppose that two meteorites representing Planets 2 and 3 (the diagram on page 42 left) formed from a common parent material having a $Rb/Sr = 0.6$ corresponding to the spectroscopically estimated value for the atmosphere of the sun. Then, regardless of changes in the value of the chemical abundance ratio of Rb/Sr during their formation, it would be possible to measure a value of $\Delta t = 2$ m.y. This time resolution corresponds to the first week in the life of a 60-year-old man. With such high time sensitivity, both from intermediate and long-lived radioactivities, an understanding of the details of the infancy of the solar system is now possible, particularly when measurements on lunar samples (and eventually on other planets, asteroids, and comets) are made.