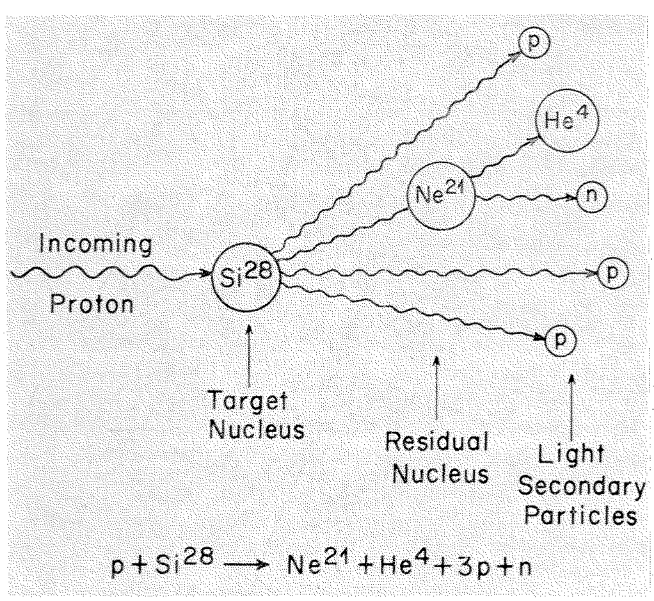
NUCLEAR PROCESSES IN METEORITES

by Donald S. Burnett

In addition to preserving a record of the effects of the decay of long-lived nuclei, meteorites can preserve a record of nuclear processes of a fundamentally different type than occur in terrestrial rock. Study of this record can lead to a nuclear history of the solar system, in the sense that it can provide information on (1) nuclear events which may have occurred during, subsequent to, or even prior to the formation of the solar system, and (2) the physical and chemical processes that have governed the evolution of meteoritic material over the lifetime of the solar system.

Although many investigations have been carried out in various laboratories, it is still too early to tell how firmly this "history" can be established. Many parts of the record are too complex or too garbled to be understandable. The sifting process that might someday lead to unambiguous results is still in progress.



The high-energy nuclear reaction illustrated above is only one of many that may occur between a cosmic ray proton and the constituent nuclei of meteorites. Cosmic ray effects in meteorites are studied by measuring the amounts of such residual nuclei as Ne^{21} *and* He^4.

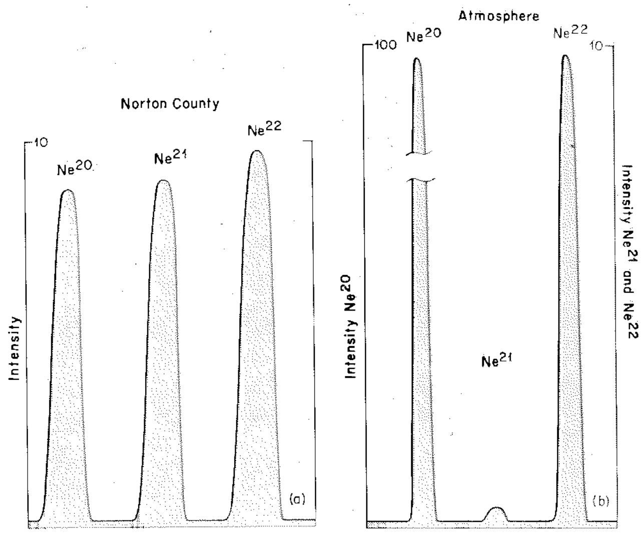
RECENT HISTORY— EFFECTS OF COSMIC RAY BOMBARDMENT

The protection from cosmic rays given to the surface of the earth by the atmosphere and the geomagnetic field does not exist for a meteorite in interplanetary space. A large fraction of cosmic ray particles (mostly protons) striking a meteorite undergo nuclear reactions with the constituent nuclei of the meteorite (left). Reactions that produce neon or other rare gas isotopes provide an important means of studying the effects of cosmic ray bombardment. At the time the minerals of the meteorite solidified any neon present in the environment was left behind because it is a gas and is chemically inert. Consequently, the neon in the vast majority of meteorites originates as the product of nuclear reactions. Although the amounts of the neon isotopes present are very small, they can be detected separately with a high-sensitivity gas mass spectrometer.

The isotopic composition of the cosmic-ray-produced neon is considerably different from that found in the earth's atmosphere. In the case of the Norton County meteorite, for example, the amount of neon observed corresponds to an exposure time to cosmic rays of roughly 0.2 billion years. On the other hand, utilizing the decay of Rb^{87} to Sr^{87}, G. J. Wasserburg, Caltech professor of geology and geophysics, and I have found that this meteorite crystallized 4.6 billion years ago. The difference in these times means that the meteorite was shielded from cosmic rays by being buried (to depths of a few yards or greater) in a larger body until 0.2 billion years ago, when it was released as a small body (most likely by collisional breakup) and subsequently fell on the earth. Similar measurements from many laboratories have shown that this conclusion is generally true for all meteorites studied to date.

ANCIENT HISTORY—PRIMORDIAL IRRADIATIONS

In addition to cosmic rays, which originate in the galaxy outside our solar system, violent flares on

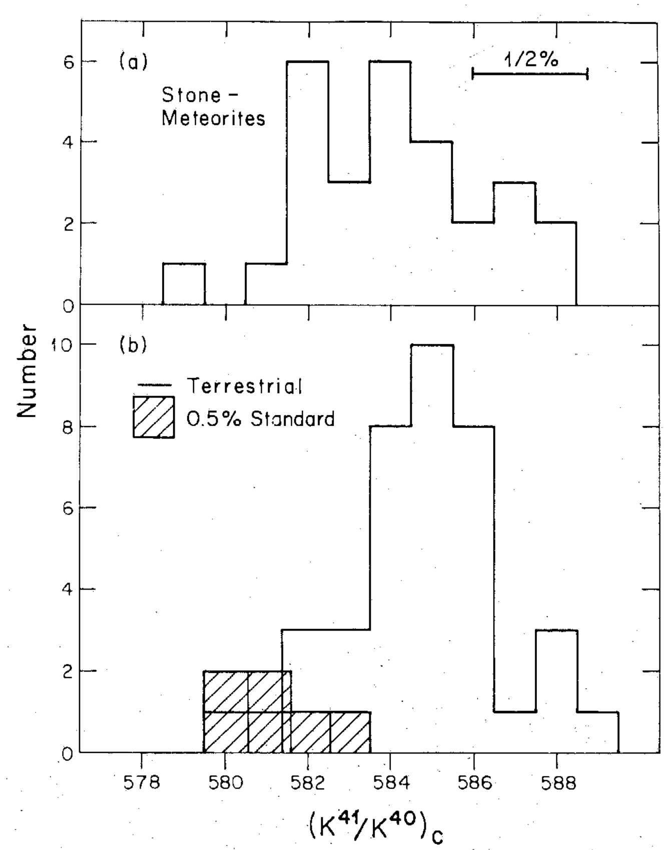


Mass spectrum of neon from the Norton County meteorite (left) and the earth's atmosphere (right). The break in the atmospheric Ne^{20} *peak is to emphasize that* Ne^{20} *is about 10 times more abundant in the earth's atmosphere than* Ne^{22}*. The neon in Norton County originates entirely from cosmic-ray-induced nuclear reactions. The amount of neon in Norton County is about* 50 x 10^{-8}cc *per gram. (Measurements made in collaboration with D. D. Bogard, P. Eberhardt, and G. J. Wasserburg.)*

the surface of the sun have been observed to accelerrate particles to sufficient energies to cause nuclear reactions. The present rate of production of solar flare particles with energies comparable to galactic cosmic rays is insufficient to produce significant effects in meteorites, but how far this conclusion can be extrapolated into the past is not known. In particular, there is some basis for speculating that the rate of particle acceleration may have been considerably higher in the past.

Astrophysical observations on objects known as T-Tauri stars indicate that these are very young (only a few million years old) and are still associated with a cloud of gas and dust from which they presumably formed. Moreover, the concentration of lithium on the surface of these stars appears to be at least 10 times greater than it is in the surrounding cloud. Lithium is an element which is thought to be synthesized by nuclear reactions resulting from stellar surface flares; thus these stars appear to be accelerating particles and synthesizing lithium. The T-Tauri stars may be evolving toward stars similar to the sun, so it is possible that the sun (and perhaps all stars) accelerated large numbers of particles in its early evolutionary phases. Whether or not meteorite investigations can shed any light on the existence of such an event depends on what is assumed about the state of the solar system at the time of irradiation.

Without discussing specific models, one can say that if the materials that eventually formed the earth and formed the meteorites had sufficiently different histories of irradiation or subsequent mixing, then variations in the isotopic composition of certain sensitive elements might result. For example, meteorites may have formed from material that was further from the sun and therefore experienced less irradiation. The very low abundance of K^{40} relative to the other potassium isotopes, K^{39} and K^{41}, and to other neighboring elements makes it quite sensitive to various types of irradiation because it takes only a small amount of reaction to produce a measurable effect in K^{40}. However, our studies showed that no difference could be observed in the isotopic abundance of K^{40} in terrestrial and meteoritic samples. Quantitative interpretation requires a more detailed discussion about the conditions of irradiation; however, no positive evidence for any large-scale particle irradiations could be found. Similar investigations in other laboratories on the elements Li, Gd, S, and Cr came to the same conclusion. But all these studies are only sensitive to *differences* in the conditions of irradiation between terrestrial and me-



The measured ratio of K^{41} *to* K^{40} *in a variety of meteoritic (a) and terrestrial (b) samples. No distinction in the* K^{41}/K^{40} *ratios in the two types of material could be detected. The sensitivity of the mass spectrometric measurements is shown by the cross-hatched squares, which are measurements of a standard which was enriched in* K^{40} *by 0.5%. (Measurements made in collaboration with H. J. Lippolt and G. J. Wasserburg.)*

teoritic material and can only place limits on the way in which such irradiations would have to occur.

NUCLEAR PREHISTORY— NUCLEOSYNTHESIS AND EXTINCT NUCLEI

Although meteorites give no evidence for strong nuclear activity within our solar system during its formation, they do contain a record of large-scale nuclear events that occurred prior to this time. The synthesis of the various chemical elements from hydrogen by chains of nuclear reactions is generally believed to occur in the interiors of stars and in supernova explosions. In addition to the stable nuclei which remain today, these processes produce a large number of unstable radioactive nuclei. Some of these, such as K^{40}, Rb^{87}, and U^{235}, decay slowly and exist in nature today. Nuclei with intermediate lifetimes can exist through the time interval following the events of nucleosynthesis until the formation of solid bodies in the solar system, but they cannot survive the intervening 4.6 billion years.

Strong evidence exists for the presence of two such "extinct nuclei"—Pu^{244} (with a half-life of 82 million years) and I^{129} (half-life of 17 million years) —when meteoritic material was formed. I^{129} decays to Xe^{129}, an isotope of the rare gas xenon. Very little xenon, like neon, was incorporated into the meteorites when they formed; the Xe^{129} formed from I^{129} decay can produce a striking excess of this isotope in meteoritic Xe. Following its discovery by J. H. Reynolds at Berkeley, excess Xe^{129} has been found in a large number of meteorites.

Fission tracks in a crystal of the mineral diopside from the Four Corners meteorite. The tracks presumably arise from the spontaneous fission decay of the now-extinct Pu^{244}. *The number of tracks shown corresponds to a density of* 6,000,000 *tracks per square cm. The dimensions of the picture are roughly 40 by 50 microns.*

Pu^{244} decays primarily by the emission of alpha particles, but about 1/1000 of the decays occur by a process known as spontaneous fission in which the Pu^{244} nucleus splits into two large comparable-sized fragments. Evidence for fission processes in meteorites has come from two independent methods:

(1) Roughly 5 to 6 percent of the fission events produce the isotopes Xe^{131-6}. As first demonstrated by Rowe and Kuroda of the University of Arkansas, there is excess Xe^{131-6} in many meteorites, which can almost certainly be attributed to fission.

(2) A large amount of energy is given to the fragment, which in turn produces a path of radiation-damaged material in the crystal in which the fission event occurs. 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" along the original path of the fission fragment. As shown by Fleischer, Price, and Walker at the General Electric Research Laboratory, several meteorites contain many more fission tracks than would be expected if Pu^{244} were not present.

The presence of these extinct nuclei almost certainly means that events of nucleosynthesis occurred in an interval of a few hundred million years just prior to the formation of our solar system. The case of I^{129} is somewhat ambiguous, since it could be formed by nuclear reactions during a large-scale irradiation within the solar system; however, corresponding reactions do not exist for Pu^{244}.

Considerable additional insight and experimental data will be needed before the full implications of the presence of the extinct nuclei can be grasped. Nevertheless, their potential usefulness appears very large.

THE ROLE OF RETURNED LUNAR SAMPLES

The moon's surface, regardless of whether it is recent or ancient, undoubtedly contains an analogous record of nuclear processes. If it is old, more information about the early history of the solar system should be obtained. If the surface is recent, it may be possible to learn about the erosional and regenerative processes that caused it to be recent. The exciting aspect of lunar-sample investigation is that, at present, no one appears smart enough to know just what to expect.