search & discovery

Material in rare meteorites may pre-date solar system

The discovery of anomalously high proportions of oxygen 16 in certain rare meteorites has led to speculation that these meteorites may contain remnants of material with a separate nucleosynthetic history from the bulk of the solar system. This material appears to be present in meteoritic inclusions that have been analyzed[1] by Robert N. Clayton, Lawrence Grossman and Toshiko K. Mayeda, all geochemists at the University of Chicago, and may represent interstellar dust grains that somehow survived the formation of the solar system without being vaporized or homogenized.

If the inclusions are in fact the result of a single nucleosynthetic event, unlike all the other homogenized matter —terrestrial and lunar—so far studied, theorists would have a good chance to test their ideas on the origin of the elements and on solar-system formation.

Cut surface of Allende meteorite with numerous light and dark inclusions that show anomalously high proportion of O^{16}. These inclusions are composed of high-temperature silicates and oxides and may have condensed directly from the solar nebula prior to incorporation into the meteorite, according to Robert Clayton, Lawrence Grossman and Toshiko Mayeda (Chicago). The O^{16} component made up 1–2% of the mass of the inclusions.

The Chicago group was studying the anhydrous high-temperature phases that occur in the meteorites known as "C2" and "C3" carbonaceous chondrites. Their interest lay in studying the condensation chemistry—the temperatures at which various minerals condensed out of the solar nebula during the formation of the meteorite. About half their samples were from the Allende meteorite, which fell in Mexico in 1969, and about half from other C2 and C3 meteorites. In determining the O^{18}/O^{16} ratio, they came upon a surprise: Chemical fractionation (mass-related variations of a few percent in reaction rates for different isotopes) should lead to small variations in the O^{18}/O^{16} ratio. But the variations in O^{18} were too large, and too little of it was present, compared with other meteorites.

Over 25 years ago Harold Urey had noted that chemical isotope effects are almost linearly proportional to relative mass differences. The Chicago group reasoned, then, that for elements with three or more isotopes, isotope effects could be used to distinguish between

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Asymptotic freedom invoked to explain SLAC scaling

Recently many particle theorists have come out in favor of asymptotic freedom instead of academic freedom, at least in the high-energy regime. Some workers had been looking for a way to use field-theoretic ideas to explain the scaling behavior found in deep inelastic electron-proton scattering at SLAC. These experiments, which involve virtual photons, allow one to measure behavior at very small distances, a feature not available in normal high-energy proton-proton scattering.

Now David J. Gross and Frank Wilczek[1] (his graduate student) at Princeton and Hugh David Politzer[2] (a graduate student of Sidney Coleman's) at Harvard, have shown that there is a class of field theories that predict phenomena close to SLAC scaling. These are genuine Lagrangian field theories in which you could compute, in a way essentially independent of perturbation theory the small-distance behavior; then you find that the strength of the interaction goes to zero. The essential features of the work had been discovered a few months earlier by Gerard 't Hooft at the University of Utrecht, but he did not publish his results. In a rough sense, such asymptotically free theories are theories in which the interactions between fields go to zero as the spatial separation goes to zero.

One cause for all the excitement is that with asymptotically free theories it is actually possible to make some detailed calculations. Then, too, Coleman and Gross have shown[3] that nonabelian gauge fields are necessary for asymptotic freedom (necessary but not sufficient, because one can build models involving nonabelian gauge fields that are not asymptotically free). A much more restricted version of the same results was found by Anthony Zee (Princeton). Such nonabelian gauge fields have been used by Steven Weinberg (Harvard) and others in an attempt to unify the weak and electromagnetic interactions. Weinberg feels that asymptotic freedom allows one effectively to study a region where the strong interactions disappear so that one can "see through to the underlying field theory." It allows theorists to do calculations about processes at suffiredundancy, frequently, whereas usually the bubble chamber has too much (one doesn't need ten bubbles per centimeter, he notes), although not always. People criticize bubble chambers because they cannot be triggered. "The beauty of the bubble chamber is that it is stupid; it takes everything." Peyrou is in favor of electronic techniques using non-destructive triggering. Some experimenters are using the bubble chamber as a target instrument; the energy is measured downstream by a spectrometer. "That slows down the data taking," Peyrou notes, "but maybe that's not unfortunate because the analysis takes too long anyhow." Such a technique is being considered for CERN.

Samios, too, feels that the present generation of bubble chambers is probably the last one. Small chambers will continue to be used as track-sensitive targets, he feels. They will be used in hybrid form, as is presently being done at NAL and SLAC. One first has a bubble chamber and then follows it with electronic equipment such as wire or drift chambers. This allows very accurate track measurements, and one can make decisions on whether or not to take a picture, depending on some electronic signal. Such hybrid devices do not require big chambers. —GBL

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chemical and nuclear processes: A reaction that produces a two-percent change in the O^{18}/O^{16} ratio should produce a one-percent change in the same direction in the O^{17}/O^{16} ratio.

When Clayton and his colleagues looked at O^{17} abundances and plotted a certain function of the O^{17}/O^{16} ratio versus the same function of the O^{18}/O^{16} ratio, they found their data fell on a straight line with a slope of one, in sharp contrast with the slope of one-half for the line linking data points from all other samples so far analyzed. The result, they conclude, indicates that different nuclear processes occurred here from those in the other samples. (Urey himself, Clayton told us, had earlier suggested that some meteorites might contain material from outside the solar system. His idea had been to search for meteorites that had had hyperbolic orbits.)

Before they speculated on a separate nucleosynthetic origin for the chondritic inclusions they considered what other nuclear processes might have led to the observed ratios. Irradiation by protons, neutrons or alpha particles, for example, could remove larger amounts of the relatively unstable O^{17} and O^{18} than of the O^{16}. But, the experimenters point out, any such reaction must have equal cross sections for the two heavy isotopes to cause the observed equal fractional depletions of both. And no peculiarities in the abundances of other elements or their isotopes have been observed, as might be expected from radiation strong enough to deplete O^{18} and O^{17} by the observed three percent.

Alternatively the samples could be a mixture of a component with the ordinary composition and varying amounts of some other component, highly depleted in O^{17} and O^{18}. This O^{16}-rich component might be the result of helium burning or of carbon burning, in our Sun or other stars. If it were derived from the Sun, the amounts of O^{17} and O^{18} in the solar wind should be relatively low. There is as yet no evidence on the abundances of these isotopes in the solar wind.

Suppose that the O^{16}-rich component in the meteoritic inclusions did come from outside the solar system. Previous evidence from isotopic abundance studies, Clayton explained to us, indicated that all matter in the solar system had passed through a stage of complete homogenization, implying that it had all been in the gaseous state. Most classic theories of solar-system evolution, therefore, have included a vaporization stage. But, Clayton points out, there is no apparent astronomical evidence that requires such a stage: "If you look at regions where stars are being formed now, you see clouds of opaque material," he told us.

The next work to be done is to analyze the meteoritic inclusions for isotopic anomalies in the other elements present, in order to determine the composition of the substance that apparently survived the high-temperature stage. The Chicago group expects to have ready a microprobe that will allow them to do elemental and isotopic analyses on a microscopic scale. They expect that magnesium and silicon will be among the elements found, both of which—fortunately—have three stable isotopes. Then, from the known condensation temperatures of these minerals, the temperature through which the solar system passed can be estimated.

Even if the isotopic composition shows that the meteoritic inclusions were solid grains before the formation of the solar system, there may be no answer to the question "How *long* before?". As Clayton explained to us: "If the material we're looking at had the kind of nucleosynthetic history that could give us enriched O^{16} without the other elements, it's very likely that this event just wasn't the one that made heavy elements, and it's the heavy elements that are used for age determinations." A. G. W. Cameron (Harvard-Smithsonian Astrophysical Observatory) is somewhat less pessimistic and expects that uranium could be present.

Cameron has invoked[2] initial variations in isotopic abundance at different parts of the primitive solar nebula as a way of explaining apparent large time differences in meteorite formation. The standard methods of dating with strontium and lead sometimes lead to differences of the order of 10^7 years in the ages of meteorites that should be about the same age. Questioning whether these age differences are real, Cameron shows how parent and daughter isotopes could have been created by separate events and undergone incomplete mixing. His estimates, however, are of a 0.1% isotopic depletion for the heavy elements he discusses, whereas the observed change for the oxygen is three percent. He also explained to us that any predictions about the O^{16}-rich component would depend on whether or not the O^{17} and O^{18} resulted from a common (nuclear) production process.

Urey has recently reconsidered the fractionation question and come up with a possible non-nuclear explanation for fractionation of O^{16} relative to O^{17} and O^{18} together, although he does not consider the process very probable. Fractionation could be photochemically induced if a narrow wavelength radiation band that happened to coincide with an absorption band for a molecule containing O^{16} (but not O^{17} or O^{18}) were to hit a gas that was in incomplete local thermodynamic equilibrium. This laser-like radiation could change the relative abundance of the O^{16} quite differently from the change caused by mass-related chemical fractionation.

Relating this process to conditions in the primitive solar nebula, Cameron explained to us that the nebula could have had regions where the mean free path for photons was comparable to the dimensions of a region with changing temperature and pressure. Accidental coincidences could occur between, say, emission bands from silicates and absorption bands of a molecule containing O^{16}. "How would you differentiate between nuclear and non-nuclear processes?" we asked. For the nuclear processes you would expect high relative C^{12} to accompany the high O^{16} because all of these would result from explosive nucleosynthesis. For the photochemical case, no such consistent relation would be expected. "Whatever the explanation, it's obviously going to tell us some very important things about nature."

— *Marian S. Rothenberg* □

References

1. R. N. Clayton, L. Grossman, T. K. Mayeda, Science 182, 485 (1973).
2. A. G. W. Cameron, Nature 246, 30 (1973).