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17 December 1962

"Ages" of the Sikhote Alin Iron Meteorite

Abstract. *Measurements of the potassium and argon content of the Sikhote Alin iron meteorite, by activation analysis, enable a potassium-argon "age" of 1.7×10^9 years to be calculated. Such an age is vastly different from all the ages previously measured for iron meteorites.*

Lead isotopic ratios showing an excess of the nuclides lead-206, lead-207, and lead-208 have been measured in several iron meteorites (*1–3*). As with such ratios reported for stone meteorites, these excesses may represent radiogenic contributions from the natural decay of uranium-235, uranium-238, and thorium-232, respectively. A lead-lead age calculated from the data, making the usual assumptions involved in the method, does indeed lead to an age of 4.6×10^9 years, in good agreement with ages calculated for stone meteorites by a variety of methods. However, in several of these meteorites there is a discrepancy between the measured uranium content and that expected from the lead content. In the Sikhote Alin meteorite, in particular, an upper limit was set to the abundance of uranium-235 which is two orders of magnitude too small to account for the excess lead-207 as radiogenic within the specified time interval (*4*).

It is not clear how to reconcile these data. It has been suggested that the lead is nonradiogenic (*1*), that radiogenic lead was added to the meteorites about 0.77×10^9 years ago (*2*), that uranium was removed from the meteorites about 0.1×10^9 years ago (*4*), or that the lead data are the result of terrestrial contamination. The data have now been reproduced by several independent observers, so it is not probable that contamination is the answer.

A suitable method for investigating the other suggestions is potassium-argon dating, since it is difficult to visualize any process which might remove uranium or add lead without melting the meteoritic material, thus removing argon as well. Such an experiment is reported here, and leads to a potassium-argon "age" of about 1.7×10^9 years. This indicates that a uranium/lead differentiation did not take place more recently than this date.

Three separate runs were made at the Brookhaven reactor, in which samples of 3 to 5 grams were irradiated for 3 hours at a flux of 5×10^{12} neutrons per square centimeter per second, together with about 200 mg of potassium chloride as a flux monitor. The samples were prepared for the irradiation by an acid bath in which approximately 20 percent of the mass was etched away. After irradiation this etching was repeated just as severely, to remove all possibility of surface contamination. The sample was placed in an alumina crucible in a vacuum line, then boiled by induction heating for 20 minutes in the presence of argon carrier. The evolved gases were passed over hot titanium, which was then cooled to remove hydrogen. The gases were then pumped into a proportional counter with a background of about 10 counts per minute (count/min). The chemical yield was 100 percent in all cases. Initial counting rates in the three samples varied from 4000 to 300 count/min. The activity followed the argon-41 half-life down to about 15 count/min, then decayed with the argon-37 half-life of 35 days for over a month. The potassium was separated from the melted mass and from the material vaporized onto the walls of the furnace by repeated ion exchange and cycles of precipitation with tetraphenyl boron. Counting was done on beta proportional counters with backgrounds of about 8 count/min. Initial counting rates varied from 7×10^5 to 2×10^4 count/min. The activity followed the potassium-42 half-life for many half-lives.

Table 1. "Ages" of iron meteorite samples. Ar_t, total argon; Ar_r, radiogenic argon.

Argon (10^{12} atom/g)			Ar^{40}_r/K^{40}	"Age" (10^9 yr)
Ar^{36}	Ar^{40}_t	Ar^{40}_r		
Sample 1, weight 2.74 g				
3.8	14.4	13.7	0.19	1.7
Sample 2, weight 3.0 g				
0.73	1.12	0.98	0.21	1.9
Sample 3, weight 4.25 g				
1.0	5.3	5.1	0.15	1.5

The argon-41 activity results from the $Ar^{40}(n,\gamma)Ar^{41}$ reaction, and gives directly the argon-40 content. A correction for cosmic-ray-produced argon-40 can be made from the argon-37 activity, which results from the $Ar^{36}(n,\gamma)Ar^{37}$ reaction. Argon-36 is produced in meteorites through direct nuclear production and through the decay of cosmic-ray-produced chlorine-36. The cross-section ratio, from iron targets, of $(Ar^{36} + Cl^{36})/Ar^{40}$ is about five (*5*). The correction for cosmogenic argon-40 in this meteorite is shown in Table 1. The observed variation of argon-41 activity with the potassium activity (see Table 1) indicates the close association of argon with potassium in the meteorite: The three samples show a total variation of a factor of 15 in potassium content, yet the potassium/argon ratio stays constant to within ± 20 percent. This potassium-argon togetherness renders unlikely the possibilities of either contamination by primordial argon or loss of radiogenic argon by diffusion. Diffusion loss is improbable also because (i) there seems to have been no such loss of cosmogenic helium, neon, or argon during Sikhote Alin's cosmic ray age of about 150 million years (*6*), (ii) no such loss of cosmogenic rare gases is observed in other iron meteorites over periods of perhaps up to 1.5×10^9 years, and (iii) several other iron meteorites selected at random show no evidence of diffusion loss of radiogenic argon during their (potassium-argon) age of up to 13×10^9 years.

The potassium-42 activity results from the $K^{41}(n,\gamma)K^{42}$ reaction. Terrestrial isotopic abundance of potassium is assumed in order to calculate the potassium-40 content. This abundance ratio can be modified probably only by cosmic-ray-produced potassium, and this can be estimated from the work of Stauffer and Honda (*7*). The correction for this meteorite is negligible.

The results are shown in Table 1. Stoenner and Zahringer have previously dated several iron meteorites by this method and obtained ages ranging from

6 to 13 × 10^9 years (8). Preliminary results from experiments run concurrently with those reported here confirm these earlier results. These larger ages are not discussed here; it is merely pointed out that the Ar^{40}/K^{40} ratios measured in Sikhote-Alin are two to three orders of magnitude smaller than those found in several other meteorites selected at random. This is taken to indicate a lower age for Sikhote-Alin.

It is not clear how to interpret this result. It could be simply the result of heating to some unknown extent at any time within the past 1.7 × 10^9 years. But if the lead excesses are radiogenic, the data define a time interval during which uranium decay contributed to the abundances of lead-207 and lead-206. Because of the absence of uranium at the present time there must have been a uranium-lead fractionation late in the meteorite's history. The potassium-argon "age" reported here indicates that this fractionation did not take place more recently than 1.7 × 10^9 years ago; specifically, the possibilities that lead was added to the meteorite 0.77 × 10^9 years ago or that uranium was removed about 0.1 × 10^9 years ago must be rejected, and the calculated lead-lead "age" of 4.6 × 10^9 years is invalid.

A calculation of the lead-lead "age" is strongly dependent on the uranium isotopic ratio in the Sikhote-Alin meteorite; this ratio has not been measured, nor is it clear how one might be able to measure it, owing to the extremely low abundance of uranium. It is therefore not possible to deduce any "ages" directly from the data; some specific and prejudicial assumptions are necessary. One particular model with which the data can be reconciled is the following. All the material of the present solar system withdrew at some time from nucleosynthesis processes, so that the isotopic abundances of uranium are the same in iron meteorites, stone meteorites, and Earth. The primordial isotopic abundances of lead are identical with those measured in the Canon Diablo meteorite (9). Radiogenic lead evolved in Sikhote-Alin from the time of its solidification until 1.7 × 10^9 years ago. Then

$$\frac{Pb^{207}}{Pb^{206}} = \frac{k(e^{\lambda_1 T} - 1)}{(e^{\lambda_2 T} - 1)}$$

where Pb^{207} and Pb^{206} are the radiogenic components only, and where k is the ratio $U/^{235}U^{238}$ at the time 1.7 × 10^9 years ago ($k = 34$). A lead-lead "age" of 2.5 × 10^9 years can then be calculated, leading to a total solidification age of (4.2 ± 0.2) × 10^9 years. This "age" is presumably analogous to the total lead-lead "ages" of stone meteorites, which cluster at (4.55 ± 0.15) × 10^9 years. It should be noted that an age calculated from the Pb^{208} data in Sikhote-Alin does not agree with this; this may be due to a Th/U ratio in the iron meteorites which is different from that in the stones and Earth. There may well be alternative interpretations of the data (10).

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6 December 1962

Sonar Signals of the Sea Lion

Abstract. *Tape recordings were made of the underwater noises of captive sea lions swimming in a concrete pool at night. When approaching pieces of fish that were thrown into the water, the sea lions emitted trains of sound signals like those of the bat and the porpoise. A detailed analysis of these noises shows that they meet the criteria of a pulse-modulated sonar system and, in fact, reveal an amazing sophistication so far as echo ranging is concerned.*

Within the past 2 years I have had occasion to make numerous visits to a small uninhabited island off the California coast (1). This island is occupied at certain times of the year by thousands of seals and sea lions. Occasionally I have seen one of these animals which, by its behavior and by such tests as I could make, appeared to be totally blind. Yet it was well fed and avoided rocks as well as other sea lions while in the water. The use of echo ranging or sonar for obtaining its food at once suggested itself.

I therefore obtained tape recordings of the underwater noises made by captive sea lions at the San Francisco and San Diego zoos. For these recordings (2) I used a magnetic tape recorder, with a barium titanate hydrophone having a resonance frequency of 125 kcy. The hydrophone was placed at one end of the pool and the pieces of fish were thrown in adjacent to a small island in the pool so that the animals could approach from either side. Since the major portion of the energy in these recordings occurred at frequencies below 20 kcy and so much work remains to be done before any reasonable analysis can be made of the high frequency components, this report deals primarily with that portion of the signals of the California sea lion, *Zalophus californianus* (Lesson), occurring below 20 kcy. Several of these animals were kept in concrete pools, with means for isolating those animals that were not involved in the recordings. Recordings were made with from one to as many as 20 animals and with light conditions ranging from daylight to so dark that the pieces of fish, and much of the time the animals, were not visible to the human eye. The sounds recorded under these conditions are quite distinct from the raucous barks which the sea lion makes in the air. They consist of a series of short pulses which are similar in many ways to the sonar pings of the porpoise as described by Kellogg (3). Since the animals will pick up pieces of fish thrown into the tank just as quickly under the darkest conditions mentioned above as they do in daylight, I believe these sounds to be echo-ranging signals of a complex and sophisticated nature. An acoustical analysis of many of these pulses was made by playing the tapes at a reduced speed through a Minneapolis-Honeywell recording oscillograph (Visicorder) model 1508, which was necessary to observe wave form and measure the fractional millisecond time intervals.

Although many different types of signals are used under different conditions, one of the most characteristic type used by the California sea lion when approaching a piece of fish in the dark has been analyzed in some detail. It is, in fact, a kind of double