Strontium-Rubidium Age of an Iron Meteorite

Abstract. *The isotopic compositions and concentrations of rubidium and strontium were determined in silicate nodules contained in Weekeroo Station meteorite, a brecciated coarse octahedrite. The strontium had a $Sr^{87}:Sr^{86}$ range from 0.729 to 0.768, showing considerable enrichment in Sr^{87} in comparison with achondrites. Data for six samples of nodules lie on a straight line on the Sr–Rb evolution diagram, with an initial $Sr^{87}:Sr^{86}$ ratio of 0.696 to 0.702; the slope is 0.0674, corresponding to an age of 4.7×10^9 years for $\lambda = 1.39 \times 10^{-11}$ year^{-1}. These data agree with the previously assigned ages for the formation of stony meteorites and the earth; they support the conclusion that the major period of chemical and physical differentiation in the solar system occurred in a narrow interval at about this time. This result disagrees with the Ar^{40}-K^{40} ages of 5 to 13×10^9 years determined from other iron meteorites. A wide variety of isotopic-age investigations now seem experimentally feasible on iron meteorites that contain silicates.*

The most precise determinations of the time of formation of solid objects in the solar system have been made by use of the long-lived radioactivities of U^{238}, U^{235}, Th^{232}, K^{40}, and Rb^{87} in meteorites and in terrestrial materials. Theoretical estimates of the lifetime of the sun on the main sequence give results that are compatible with these determinations but are much more uncertain (*1*). The minimum time scale for the solar system is determined by the maximum "age" of its constituent members. Extensive studies of ages of terrestrial rocks have produced many well-documented ages of about 2.8×10^9 years and rather strong evidence for rocks which are about 3.5×10^9 years old (*2*). The only extraterrestrial objects that are currently available for laboratory investigation are meteorites—the most ancient bodies found to date.

Based on a principle outlined by Houtermans (*3*), the determination of the isotopic composition of lead in iron meteorites by Patterson, Brown, Tilton, and Inghram and by others (*4*) has provided the basis for calculating the time required for lead in "modern" terrestrial rocks to evolve from lead of the isotopic composition found in iron meteorites. This time is frequently called the "age of the earth." By use of lead in recent basalts and in modern ocean sediments in conjunction with the iron-meteorite data, the calculated age is 4.55×10^9 years (*5*). In this calculation one must assume that the samples of modern terrestrial leads have evolved in a system in which lead and uranium are not chemically fractionated. Patterson (*5*), in a study of lead in three stony meteorites, showed that these data lie on a straight line on the common lead-evolution diagram ($\beta = Pb^{207}:Pb^{204}$ versus $\alpha = Pb^{206}:Pb^{204}$), passing through the iron-meteorite point. These results indicate that the same time was required to evolve the lead in stony meteorites and in the earth from the lead in iron meteorites. However, studies of samples of modern terrestrial lead (*6*) indicate a rather complicated history of lead-uranium fractionation during the evolution of the earth's crust. Moreover, the stony-meteorite data show an unsatisfactory material balance for lead-uranium and thorium, and variations in the lead composition of iron meteorites are reported (*7*).

Precise determination of Ar^{40}-K^{40} ages in some stone meteorites (*8*) showed ages ranging to a maximum of 4.4×10^9 years. These results showed that many of these objects were not significantly heated or chemically altered during this time. Studies of Sr^{87}-Rb^{87} ages of stony meteorites (*9*) showed that a wide variety of stone meteorites lie on a straight line on the Sr–Rb evolution diagram ($Sr^{87}:Sr^{86}$ versus $Rb^{87}:Sr^{86}$), again indicating a common age of differentiation at about 4.6×10^9 years.

All of the preceding ages are subject to uncertainties of about 0.2×10^9 years because of analytical errors, errors in the half lives, and possible complexities in the chemical history of the objects. Nonetheless, the body of data indicates that the time of 4.3 to 4.7×10^9 years is a "magical" period in the early history of the solar system. Some data from terrestrial samples and from some stone meteorites seem to suggest ages somewhat greater than the magic number, but these remain to be substantiated (*10*).

The only major anomaly that currently exists is the apparent Ar^{40}-K^{40} ages from certain iron meteorites (*11*); the ages ranged from 5 to 13×10^9 years. The iron meteorites are especially important because it is exceedingly unlikely that they are derived from the moon-earth system; they represent distinctive samples of material, although the works of Urey (*12*) and Arnold (*13*) indicate that a lunar origin of stone meteorites cannot be ruled out.

The existence of iron meteorites for 10×10^9 years would have serious implications for the history of the solar system and of the galaxy as a whole. The processes by which the elements were synthesized very likely have not been the same at various points in space and time during the history of the galaxy (*14*). Thus, in general, if the irons existed as solid bodies for 5×10^9 years prior to formation of the solar system, one would expect variations in the isotopic abundances of many elements, assuming that nucleosynthesis has been continuous during the history of the galaxy. But many experimental investigations have shown that this is not true: in particular the measurements of Burnett, Lippolt, and Wasserburg (*15*) showed no differences (to within 1 percent) in the isotopic abundance of K^{40} among terrestrial standards, stony meteorites, a mesosiderite, and silicate inclusions from the Weekeroo Station iron meteorite. Potassium-40 has a relatively short half life of 1.3×10^9 years; thus bodies made from elements that were isolated from the intersteller medium at times differing by 5×10^9 years would be expected to have different K^{40} abundances, even if the elements have always been synthesized with the same isotopic composition throughout the history of the galaxy. Thus it is very unlikely that the iron meteorites had a distinct origin in time from other solar-system objects. Moreover, Burnett *et al.* reported that the isotopic composition of Rb in Weekeroo Station silicate was the same as that found in terrestrial minerals, to within 2 percent. The straightforward interpretation of the uniformity of isotopic abundances is that, if the iron meteorites are indeed 10×10^9 years old, the material of the earth and the stone meteorites—and presumably of the whole solar system—has been isolated from events of nucleosynthesis during the same period. From this point of view, the ages of 4.5×10^9 years merely represent the most recent major upheaval of a much longer evolutionary time scale.

Furthermore, if the time scale of 10×10^9 years is correct, one must conclude from the lead-isotopic data for iron and stony meteorites and for the earth that U and Th were in negligible abundance in this material—and probably in all material of the solar system—until about 4.5×10^9 years ago, at which time the U and Th were added. This conclusion implies that either an event of nucleosynthesis took place at this time (that did not significantly alter the isotopic abundances of Pb, Rb, and K) or that the U and Th were highly concentrated in the earth and in the stone meteorites at this time by chemical fractionation. The latter alternative probably means that the true solar-system abundance of U and Th, relative to Pb, would have to be very small in order that there would be no significant evolution of primordial lead between 10 and 4.5×10^9 years ago in the material of the earth and of the stone meteorites. In this connection it is interesting to note that the carbonaceous chrondrites, which are considered by some to chemically approximate the primordial material, contain Pb having an isotopic composition very close to that of primordial lead from iron meteorites (*16*).

The only other previous workers who attempted to date the formation of iron meteorites were Herr *et al.* (*17*), who measured the ratios Os^{187}:Os^{186} and Re^{187}:Os^{186} in 14 iron meteorites. Their data formed an approximately linear array on the Os–Re evolution diagram. The difficult nature of the analyses, and the great uncertainty in the value of the decay constant (*18*), made precise determination of the age impossible, but, as indicated by Herr *et al.* (*17*), their results are compatible with an age of 4 to 5×10^9 years.

In all the age determinations discussed above, it should be noted that the only connection between iron meteorites and other bodies is that the lead-isotopic composition of iron meteorites is assumed to represent the original lead of stony meteorites and of the earth.

During our investigation of potassium (*15*) it became obvious that its high concentration in silicate inclusions in Weekeroo Station should permit determination of a Sr^{87}-Rb^{87} age on this and probably on other iron meteorites. For this purpose silicate inclusions were separated from a slab (about 40 by 12 by 2 cm) of this meteorite from the Harvard Collection (3.35 kg).

Weekeroo Station is a brecciated coarse octahedrite, with nodular silicate

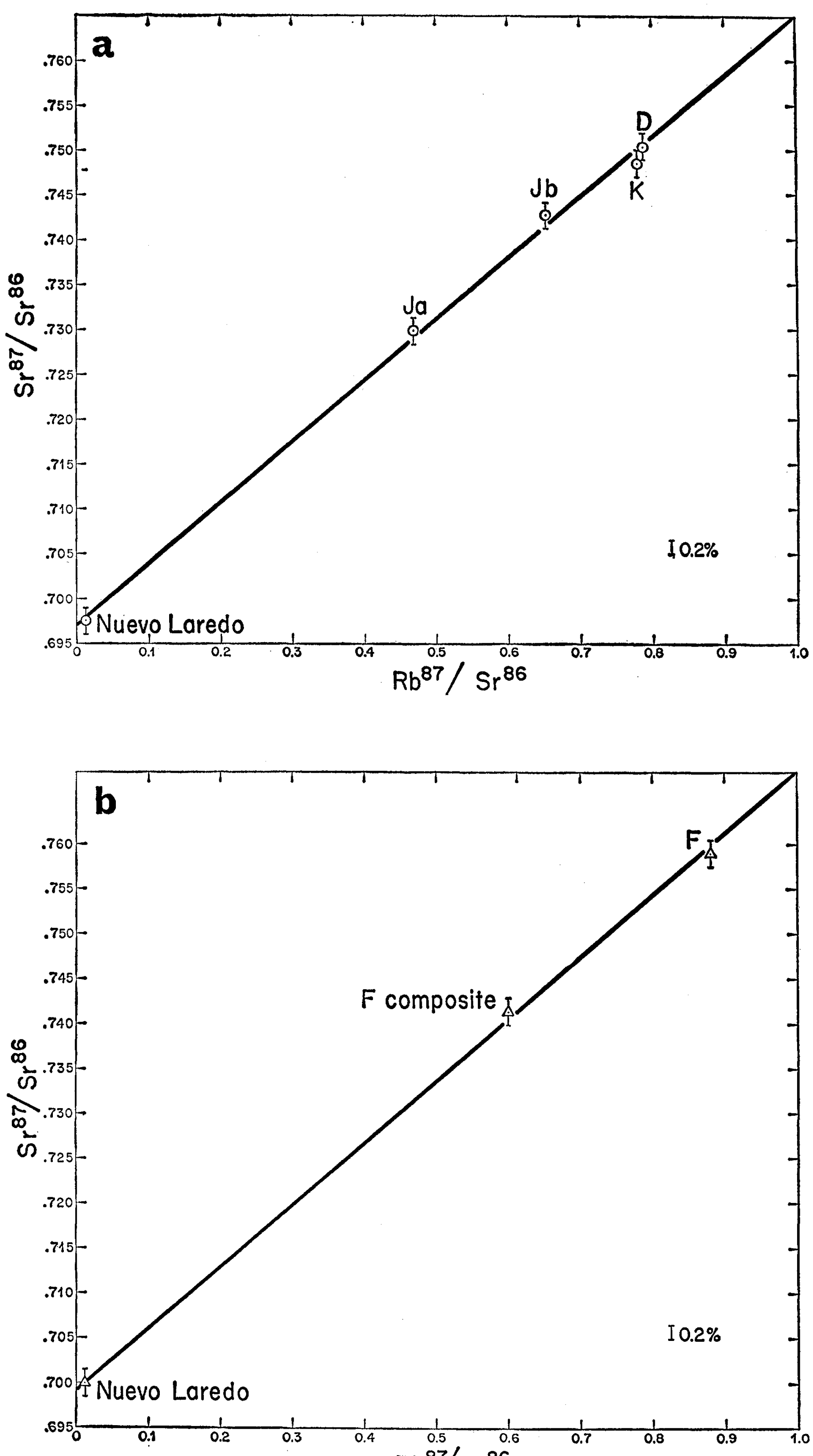

Fig. 1. *a*, Strontium-rubidium evolution diagram for four samples (*D*, *J*a, *J*b, *K*) of Weekeroo Station meteorite and a sample of Nuevo Laredo achondrite; an electron multiplier was used as detector (MS-1). *b*, Strontium-rubidium evolution diagram for two samples (*F*, *F composite*) of Weekeroo Station meteorite and a sample of Nuevo Laredo achondrite; a Faraday cage was used as detector (MS-2). The slope of the line drawn through the points is very nearly the same as that drawn in *a*, but the lines are offset by about 2 parts in 700 as can be seen by comparing the Sr^{87} : Sr^{86} intercepts.

Table 1. Strontium and rubidium analyses of silicate inclusions in Weekeroo Station meteorite and of standards [of which the sample numbers correspond to those given by Burnett *et al.* (*15*)]. MS1 and MS2 indicate analyses by mass spectrometers equipped with electron multiplier or Faraday cage, respectively. Degrees of precision: Sr^{87}:Sr^{86}, within about 0.0015; Rb^{87}:Sr^{86}, within about 1.5 percent.

Nodule		Concentration (10^{-7} mole g^{-1})		Sr^{87}:Sr^{86}	Rb^{87}:Sr^{86}
No.	Sample wt (g)	Strontium	Rubidium		
		Weekeroo Station			
I (MS1)	0.274	43.7	-	0.7678	-
F (MS2)	.047	4.50	1.40	.7591	0.8813
D (MS1)	.032	4.65	1.30	.7504	.7879
K (MS1)	.096	4.38	1.21	.7485	.7823
F composite (MS2)	.064	4.99	1.06	.7414	.6000
*Ja** (MS1)	.129	4.69	0.780	.7295 .7298	.4694
Jb (MS1)	.031	4.62	1.08	.7426	.6597
		Blanks			
Blank 1		0.00097	0.00015		
Blank 2		.0011	.00006		
Blank 3		.00088	.00013		
		Nuevo Laredo (achondrite)			
MS1		9.58	.043	.6980	.013
MS2		-	-	.7005 .6987	- -
By Gast (*9*)		9.63	.042	.7006	.013
		Sea water			
MS1				.7072	
MS2				.7087	
By Faure *et al.* (*28*)				.7093	

* Nodule elongated, with a small neck extending to the original cut surface. The larger, interior piece is *a*; the neck is *b*.

and troilite inclusions, found in South Australia in 1924. Hodge-Smith (*19*) described the bulk composition as 91.40 Fe, 6.89 Ni, 0.46 Co, 1.02 S, 0.01 C, 0.79 silicates, and traces of P; total, 100.57. The meteorite contains numerous, rather evenly distributed, small, nodular or elongate, inclusions of both silicates and troilite. A section, 49 by 19 cm, examined by Hodge-Smith contained 324 such inclusions; Rosiwal analysis of this section gave troilite and silicates about 3 and 0.8 percent, respectively.

When freed from the matrix the silicate nodules have a spheroidal or irregularly round shape and a smooth surface. The size ranges from a few millimeters to a few centimeters in length for narrow, elongate objects (as seen in section). The nodules appear to have been liquid droplets that were either individuals or, more commonly, partly coalesced aggregates of more-or-less distorted spheroids that appear peanut-like when paired or when forming bulbous aggregates of three or more individuals. Seen in section, the aggregates seem to be more-or-less drawn out, presumably as a result of mechanical deformation or flow in the matrix while the droplets were still liquid.

The silicate nodules are eucrite-like in composition and consist chiefly of plagioclase and a green clinopyroxene, with tridymite, chromite, and glass as accessory constituents. Nickel-iron and troilite are lacking within the nodules. The feldspar is approximately Ab 85 (sodic oligoclase) in composition; it does not show distinct cleavage or twinning. The $2\theta(1\bar{3}1)$–$2\theta(131)$ separation is 1.75 degrees, somewhat lower than in high-albite and representing an intermediate structural state. The feldspar constitutes about half of the nodules; the remainder is mainly unusual monoclinic pyroxene, probably a sodian subcalcic augite, that in part contains exsolution laminae of another monoclinic pyroxene. This pyroxene differs from pigeonite in having a much larger 2V and in being optically negative. It has α, 1.682; β, 1.695; γ, 1.703; it is weakly pleochroic in pale-green (γ) and yellow.

In sampling (*15*), thin slices of this meteorite were cut with an Al_2O_3 wheel and the silicate nodules were punched out. The samples were rinsed in 2.5*N* HCl and H_2O at room temperature and dissolved in HF and $HClO_4$; Rb and Sr were separated by an ion-exchange procedure. All laboratory ware used was of platinum, Teflon, or polyethylene, apart from Pyrex ion-exchange columns and pipettes. A series of blanks, run along with the experiments, consistently yielded less than 0.01 μg Sr and 0.001 μg Rb—typical blanks obtained in this laboratory (*20*). The minimum amounts of Sr and Rb analyzed in these experiments were 1 and 0.1 μg, respectively. The concentrations and isotopic composition of Sr were determined by use of a Sr^{84} tracer, and the data were normalized to Sr^{86}:Sr^{88} = 0.1194. Samples were totally spiked for Rb and Sr during the dissolution. The isotopic analyses were done by single-filament surface ionization on a tantalum ribbon, with a mass spectrometer of 30-cm radius of curvature. The first series of experiments was done on an instrument with an electron multiplier as detector; the second series, on a similar instrument with a simple Faraday cage as detector. Small systematic differences were observed for standards run on the two instruments, presumably resulting from nonlinearities in the electron-multiplier system. No difficulty with Rb background was observed when the data were taken. Tracer calibrations were repeated during the course of these experiments. Samples of sea water and of the achondrite Nuevo Laredo were analyzed as controls.

The data, including replicate mass-spectrometric analyses of some samples, appear in Table 1; the errors indicated for isotopic ratios are mean deviations. Sample I was from a separation obtained in the course of the potassium experiments and only the Sr determination could be made. The enrichment in Sr^{87} (in sample I) is very great, exceeding that found in any stone meteorite with the exception of Beardsley. The other nodules gave significant enrichments which are sufficiently variable to indicate that, with some effort, it should be possible to obtain mineral separates with even greater variations in Sr^{87}:Sr^{86}. The data on the silicate phases of Weekeroo Station, plotted in Fig. 1, *a* and *b*, lie on straight lines with a high degree of precision. The two lines are shifted by about 2 parts in 700 but have very nearly the same slope (0.0674), indicating the same age to within experimental error. From these data alone one may conclude that the initial Sr^{87} : Sr^{86} is most reasonably between 0.702 and 0.696, and that the age determined is $4.7 \pm 0.3 \times 10^9$ years. This isochron was obtained on a single meteorite; no genetic relation was assumed between different meteorites to calculate this age.

If we assume that Nuevo Laredo and Weekeroo Station are cogenetic, the data from Nuevo Laredo can be included in the determination of the slope, giving an age of $4.7 \pm 0.1 \times 10^9$ years for $\lambda = 1.39 \times 10^{-11}$ year^{-1} (*21*). Because of the analytical errors inherent in this work, and of the uncertainty in the decay constant of Rb^{87} ($\sim$5 percent), one cannot measure this time very precisely. Within the analytical errors this result is in good agreement with the Sr-Rb results reported for stony meteorites (*9*) and with the other ages discussed.

If one assumes that the results for Weekeroo Station are applicable to all iron meteorites, this age clearly disagrees with the apparent Ar^{40}-K^{40} ages of 5 to 13×10^9 years reported (*11*). A Rb^{87}-Sr^{87} age measures the last time that the Sr isotopic composition was uniform in all phases of the material. The droplet-like appearance of the inclusions discussed above suggests that there were originally two immiscible liquids from which, upon cooling, the iron crystallized before the silicates because the melting points of albite and of the albite-clinoenstatite eutectic are below that of Ni-Fe. Considering the relatively rapid cooling of bodies having radii of up to 100 km, one would expect the times of solidification and cooling of the iron and silicate phases—and consequently the time of Sr isotopic equilibration—to be less than about 10^8 years after formation. This point, and the concordance of our results with those of other workers, strongly imply that this age dates the time of differentiation and crystallization of the Weekeroo Station iron meteorite. More Rb^{87}:Sr^{87} ages must be determined in order to show that this conclusion may be extended to all iron meteorites, especially to those iron meteorites in which the great apparent Ar^{40}-K^{40} ages have been measured. Our results strongly suggest that the excessive Ar^{40}-K^{40} ages observed in iron meteorites are not a measure of the time of solidification or differentiation of these bodies, but represent occlusion of radiogenic Ar during impact (after migration by diffusion from the site of production), contamination with terrestrial argon, occlusion of primordial argon, or a production ratio of Ar^{40}:Ar^{36}, by cosmic rays, considerably higher for some iron meteorites than the ratio normally observed (*22*). We consider the last two alternatives quite unlikely from consideration of nuclear systematics and abundances and of possible spallation reactions, respectively.

Our work further emphasizes the significance of the date of about 4.4 to 4.7×10^9 years as the time of an event of major importance in the solar system. From the independent dating of stony meteorites and of iron meteorites and the coupled dating of the earth and iron meteorites, it appears that the most significant period of chemical differentiation—coupled with the formation of solid objects within the solar system—occurred about 4.6×10^9 years ago within a narrow time band (less than 0.2×10^9 years). The significance of this period is enhanced by the observation of radiogenic Xe^{129} in meteorites from I^{129} decay ($T_{\frac{1}{2}}$, 1.6×10^7 years; *23*), and of $Xe^{131-136}$ (*24*) and excess fission tracks (*25*) attributed to the spontaneous fission of Pu^{244} ($T_{\frac{1}{2}}$, 7.6×10^7 years). It is possible that I^{129} was formed by particle irradiation within the solar system (*26*), but such formation seems impossible for Pu^{244}. These observations thus indicate that the physical and chemical differentiation which took place about 4.6×10^9 years ago occurred soon after isolation of our solar system from nucleosynthetic processes in which heavy elements, including transuranics, were produced. Consequently, this time also dates the separation of the solar system from the interstellar medium, because the time scale for the evolution of the solar system, from the interstellar medium, is required to fall within a few half-lives of Pu^{244}. More precise determinations of ages by use of well-established techniques may help to clarify some of the anomalies which exist for stone meteorites (*10*). Refined measurements of the half life of Rb^{87} will aid in more accurate determination of the time scale (*27*).

Our study indicates that the investigation of silicate inclusions in iron meteorites has considerable possibilities. In addition to palasites, silicates are found in many iron meteorites including Weekeroo Station, Toluca, Odessa, Linwood, Kodaikanal, Four Corners, Copiapo, Colomera, Woodbine, Cosby's Creek, Sanderson, and Pine River. Because of their relative rarity, these inclusions must be used conservatively for maximum retrieval of data. By use of a vacuum distillation procedure in pure SiO_2 glass with a cold finger, it should be possible to determine the contents and isotopic compositions of the rare gases; and also, by subsequent dissolution and analysis of the sublimate, to determine Rb, Sr, K, and, possibly, Pb and U.

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Germination of Lily Pollen: Respiration and Tube Growth

Abstract. *Germinating pollen of* Lilium longiflorum *(cv. Ace) briefly exhibited a high rate of respiration before pollen tubes began to grow. A second period of high respiration occurred while tubes were growing. Between these periods respiration proceeded at a lower rate. Respiration was stimulated by 2,4-dinitrophenol to occur at approximately the same rate in all three periods.*

Studies of respiration in germinating pollen may reveal the timing of metabolic events important to germination. In conjunction with the studies it is necessary to establish the time of pollen tube initiation. Also, tube initiation must be reasonably well synchronized in the population of germinating pollen grains.

Tupy measured growth and oxygen uptake of apple pollen germinating in several sugars (*1*). The rate of respiration increased during the first 2 hours and then remained constant until 6 hours after pollen was placed in a sucrose solution. Tupy reported that tube elongation continued at a constant rate during the 6-hour period. The time of tube initiation was not indicated, however. The initial period of germination was not studied since measurements of respiration and tube length began 30 minutes and 3 hours, respectively, after pollen was placed in the culture medium. Brewbaker and Kwack also reported that pollen tubes elongate at a constant rate (*2*).

The patterns of respiration and tube growth in germinating lily pollen [*Lilium longiflorum* (cv. Ace)] are reported here. Anthers were removed each morning from freshly opened flowers and placed in a desiccator at about 24°C. At the end of the day anthers were removed from the desiccator and stored at 1° to 3°C. The pollen was used within a week. Oxygen uptake was measured manometrically at 30°C, and air was the gas phase. The standard culture medium was a modification of media used by others (*3, 4*). It contained, per liter of deionized water: sucrose, 290 mmole; $Ca(NO_3)_2$, 1.27 mmole; H_3BO_3, 0.162 mmole; KNO_3, 0.990 mmole; KH_2PO_4, 3.0 mmole; and tetracycline, 10 mg. The *p*H of the culture medium was 5.2.

Data for percentage germination and average lengths of pollen tubes were obtained from photomicrographs. Samples of pollen were removed from shaking flasks at 15- or 30-minute intervals, and photomicrographs of three fields were taken at each removal. The total numbers of grains and of pollen tubes at each time were used to calculate percentage germination. Data for average tube length was obtained from a map measure; lengths of individual tubes were not recorded. The average number of pollen grains per Warburg flask was calculated after the grains in replicate 0.005-ml portions of culture medium had been counted.

Most tubes began to grow between 30 and 75 minutes after pollen grains had been placed in the medium (Fig. 1). Germination increased from 2 to about 75 percent during this period; a small percentage increase may have occurred between 75 and 120 minutes. The average rate of pollen tube elongation was constant in the period after 75 minutes, but for the period of growth before 75 minutes, while percent germination was increasing rapidly, the average rate was lower. The lower average growth rates may have resulted from the continuous appearance of short, newly initiated pollen tubes and not from variations in growth rates of individual tubes.

Pollen respiration remained approximately zero until the culture medium was tipped in from the sidearms of Warburg flasks. Respiration after tipping was characterized by three distinct phases (Fig. 2), which were always observed in similar experiments.

Phase 1. Respiration increased rapidly until about 10 minutes after tipping, and the rate remained high until about 30 minutes after tipping. Very little pollen tube initiation occurred during this phase.

Phase 2. After 30 minutes respiration decreased 38 percent and remained relatively low until about 60 minutes. Considerable pollen tube initiation occurred during this phase.

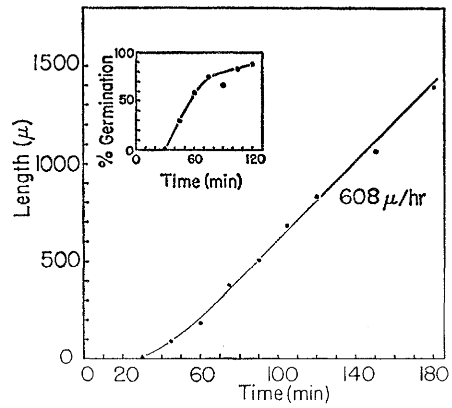

Fig. 1. Percentage germination (inset) and average tube lengths of germinating lily pollen. Data is from photomicrographs taken at the times indicated. Each value for percentage germination was calculated from counts of 133 to 256 pollen grains. Each estimate of tube length represents an average from 44 to 148 pollen tubes, except the estimate at 30 minutes, when only 3 tubes were observed. Experimental conditions were similar to those described for Fig. 2.

Phase 3. Respiration increased in the period from 60 to about 120 minutes and remained high thereafter. Some tube initiation occurred early in this phase, while respiration was increasing. Tube growth continued throughout phase 3.

Further experiments were conducted to determine the basis of this respiratory pattern. Pollen was incubated in the standard culture medium, and 2,4-

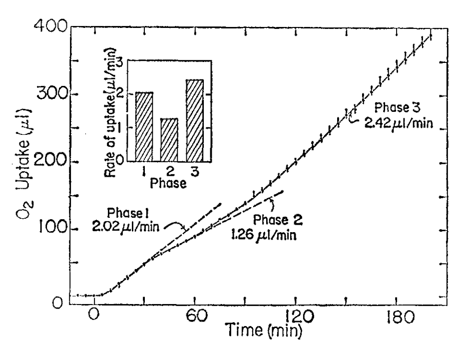

Fig. 2. Oxygen uptake of germinating lily pollen. Each point is the average of four replicate Warburg flasks, and vertical bars show extent of variation among replicates. Each flask contained 10 mg (fresh weight) pollen, representing 44,900 ± 2400 ($\bar{X} \pm S_{\bar{x}}$) pollen grains and 1.7 ml of culture medium. Time is expressed in minutes before or after addition of culture medium to pollen. The temperature was 30°C.