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EVIDENCE FOR ^{26}AL IN THE SOLAR SYSTEM

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We review the evidence for the presence of short lived ^{26}Al ($\tau_{1/2}$ = 0.72 x 10^6 years) in the early solar system. Large excesses of ^{26}Mg of up to 5% have been found in Ca-Al rich inclusions of the Allende meteorite. The Mg excesses correlate well with $^{27}Al/^{24}Mg$ and in two cases they are found in high purity separates of coarse grained Al-rich minerals which tend to exclude Mg. The data demonstrate that ^{26}Al was present in the early solar system. Mechanisms for addition of ^{26}Al to the solar nebula or for production within an active solar system are required within a few million years of condensation of small (centimeter sized) objects. The ^{26}Al abundance in Allende inclusions is high enough to provide for effective melting of kilometer size bodies or larger, if such bodies accreted early enough (a few million years) to incorporate the ^{26}Al.

We review here recent experimental data on Mg isotopic abundance anomalies and the evidence for the presence in the early solar system of now extinct ^{26}Al. The presence of ^{26}Al, with a half-life of only 0.72 x 10^6 years, would have important consequences as an indicator of nucleosynthetic processes essentially at the time of condensation in the solar system and would provide a chronometer at that time with a resolution better than 10^5 years. In addition, ^{26}Al would provide an effective heat source if it were incorporated in planetary bodies, as first proposed by Urey (1955) in his search for candidate heat sources to explain abundant evidence of melting and differentiation in ancient meteorites.

The first search for ^{26}Mg anomalies from ^{26}Al decay yielded positive results (Clarke, de Laeter, Schwarcz and Shane 1970). Following this report, however, Schramm, Tera and Wasserburg (1970) developed high sensitivity and high precision techniques for measuring Mg isotopic abundances and showed that terrestrial, lunar and ordinary meteoritic materials yield no detectable isotopic anomalies and that the earlier report by Clarke *et al.* (1970) was in error. Small isotopic effects in Mg which are not attributable to mass dependent isotopic fractionation were discovered more recently in whole inclusions of the Allende meteorite which are enriched in refractory elements (Lee and Papanastassiou 1974; Gray and Compston 1974). These small effects were evident after correction for well known fractionation effects in the thermal ionization source of the mass spectrometer and possibly in nature. For the case of Mg, which has only three isotopes, normalization of one isotopic ratio permits the identification of possible variations in the second ratio which are not the result of mass fractionation and are therefore the result of nuclear effects. However, for small nuclear variations as compared to mass fractionation effects, it is not possible to identify which particular isotope abundance is anomalous.

From the work of Lee and Papanastassiou (1974) and of Gray and Compston (1974) it was not possible to establish which particular Mg isotope had a non-normal abundance, although the latter authors preferred to interpret their results as indicating a ^{26}Mg anomaly. More extensive searches in Allende inclusions have been pursued by us in order to find *large* Mg isotopic anomalies and in order to identify possibly large inclusions with anomalous Mg, on which a variety of experiments become possible.

The results of these searches (Lee, Papanastassiou and Wasserburg 1976a,b; 1977) demonstrate that large Mg isotopic anomalies exist which are due to an excess in ^{26}Mg. These effects can therefore be caused a) by the decay within the inclusions (*in situ*) of ^{26}Al; or b) by mixing of normal solar system materials with extraordinary grains which at one time contained ^{26}Al, but which contained only the decay product $^{26}Mg^*$ at the time of their incorporation in the solar system. Before presenting the experimental data, we discuss the expected systematic behavior for inclusions and mineral phases which incorporated ^{26}Al or $^{26}Mg^*$ when they formed.

a) *In situ decay of ^{26}Al.* Let us assume that ^{26}Al was present in the solar nebula and was incorporated in condensing small objects (about 1 cm in size). We also assume that mineral phases (p) within an object with different Al/Mg have initially a uniform isotopic composition, *e.g.*, $(^{26}Al/^{27}Al)_o$ and $(^{26}Mg/^{24}Mg)_o$. This requires uniform isotopic composition in the condensing nebula (at least locally) and relatively fast condensation ($\lesssim 10^5$ years) of the phases. Alternatively, soon after condensation and prior to the decay of ^{26}Al, condensed materials were remelted and the phases achieved uniform isotopic compositions. If the phases have subsequently remained undisturbed, then measured isotopic and elemental ratios today would follow the "isochron" relationship (Lee, Papanastassiou and Wasserburg 1976a).

$$(^{26}Mg/^{24}Mg)_p = (^{26}Mg/^{24}Mg)_o + (^{26}Al/^{27}Al)_o\ (^{27}Al/^{24}Mg)_p .$$

This represents a straight line on the ^{26}Al evolution diagram (Fig. 1) which is a plot of the experimentally determined quantities $(^{26}Mg/^{24}Mg)_p$ and $(^{27}Al/^{24}Mg)_p$. The slope corresponds to $(^{26}Al/^{27}Al)_o$ and the intercept with the y-axis yields the initial $(^{26}Mg/^{24}Mg)_o$.

For a second object (phases p') formed at a later time τ and from the same reservoir (R) we obtain

$$(^{26}Mg/^{24}Mg)_{p'} = \left[(^{26}Mg/^{24}Mg)_o + (^{26}Al/^{27}Al)_o\ (^{27}Al/^{24}Mg)_R\ (1-e^{-\lambda\tau})\right] + \left[(^{26}Al/^{27}Al)_o\ e^{-\lambda\tau}\right] (^{27}Al/^{24}Mg)_{p'}$$

where the square brackets permit easy identification of the new intercept and new (less steep) slope. We note that, for the reservoir R having a solar $^{27}Al/^{24}Mg \approx 0.1$, the change in initial $(^{26}Mg/^{24}Mg)$ is extremely small for estimates of $(^{26}Al/^{27}Al)_o < 10^{-3}$. To obtain intercepts higher than for normal solar system material, $(^{26}Mg/^{24}Mg)_\oplus$, reservoirs with high $(Al/Mg)_R$ are required; furthermore, we would not expect experimental data to yield *initial* $^{26}Mg/^{24}Mg$ less than $(^{26}Mg/^{24}Mg)_\oplus$. For objects which remelted after ^{26}Al had decayed, the isochron becomes a horizontal line with a y-axis intercept greater than $(^{26}Mg/^{24}Mg)_\oplus$ only if the remelted materials had a high bulk $^{27}Al/^{24}Mg$.

b) Mixing of $^{26}Mg^*$ after ^{26}Al decay. We consider the case where the decay product $^{26}Mg^*$ is present in interstellar grains and where these grains are mechanically mixed in solar system condensates without isotopic or chemical exchange. This case does not require the presence of ^{26}Al in the early solar

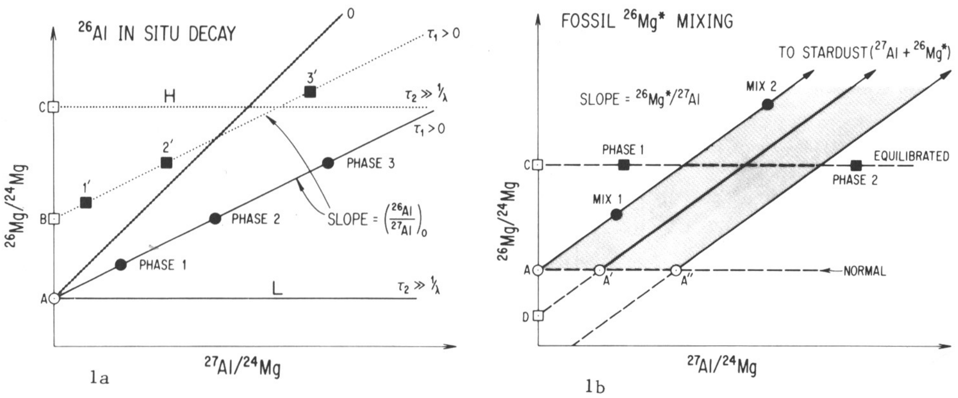

Figure 1a. *^{26}Al-^{26}Mg evolution diagram for in situ ^{26}Al decay. Straight lines are obtained for coexisting phases which at the time of crystallization incorporated Al and Mg with uniform initial isotopic compositions. Horizontal lines indicate formation after decay of ^{26}Al. H an L refer to a high and low Al/Mg reservoir R.*

Figure 1b. *Mixing of fossil $^{26}Mg^*$. Except for special cases, data will fall in an area and will not define a straight line. Note possible extrapolation of data to point D on the y-axis which is below the normal $(^{26}Mg/^{24}Mg)_\odot$ (point A).*

system, but permits the observation of ^{26}Mg effects. The simplest mixing model involves interstellar grains which contained originally, no Mg but only Al. At the time of their incorporation in the solar system, the grains contained $^{26}Mg^*$ and ^{27}Al. For mixtures involving solar system materials with $(^{27}Al/^{24}Mg) \approx 0$ we obtain a straight line on the ^{26}Al evolution diagram (Fig. 1b) with an intercept at $(^{26}Mg/^{24}Mg)_\odot$ (point A) and slope equal to $^{26}Mg^*/^{27}Al$ in the interstellar grains. If we consider solar system condensates with significant $(^{27}Al/^{24}Mg)$ (points A', A") then mixtures with the interstellar grains will define not a line, but an area on the evolution diagram. Furthermore, although measured $^{26}Mg/^{24}Mg$ would not lie below $(^{26}Mg/^{24}Mg)_\odot$, intercepts with the y-axis would yield values less than $(^{26}Mg/^{24}Mg)_\odot$.

We now consider the experimental data. Fig. 2 shows histograms of *raw* Mg isotopic ratios prior to correction for instrumental mass fractionation (Lee, Papanastassiou and Wasserburg 1976a). The distribution for normal samples includes all runs of a variety of terrestrial samples and of an ordinary meteorite. The distributions are nearly normal with a standard deciation of 0.1% for $(^{25}Mg/^{24}Mg)$ and 0.2% for $^{26}Mg/^{24}Mg$ where the difference in the standard deviation for the two distributions clearly reflects the isotope mass difference (Δm = 1 and 2 amu) for the respective ratios. Sample BG 2-6 from Allende shows a distribution for $^{25}Mg/^{24}Mg$ indistinguishable from the distribution for the normals and a clearly resolved $^{26}Mg/^{24}Mg$ and enriched by 1.3%. This is the first data which established for raw ratios a Mg isotopic anomaly due to an excess of ^{26}Mg. In Figure 3a, b, c, d we show ^{26}Al evolution diagrams for four inclusions from Allende. These are BG 2-6, BG 2-13, WA and B30. The data are from Lee *et al.* (1976a,b; 1977). All inclusions have normal $^{25}Mg/^{24}Mg$; the first three inclusions show phases with large ^{26}Mg enrichments of 1.3%, 0.8% and ~10%. For all samples there is a strong correlation of the isotopic excess with $^{27}Al/^{24}Mg$. In our search for ^{26}Mg effects we have concentrated our efforts in isolating Al minerals which effectively exclude Mg, *e.g.*, anorthite ($CaAl_2Si_2O_8$). For inclusion BG 2-6, the sample was small (3 mg) and fine-grained and did not easily permit sampling

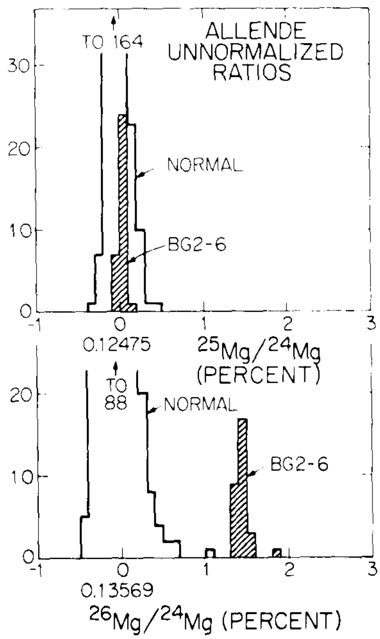

Figure 2. *Histograms of raw Mg isotopic ratios, i.e., prior to correction for instrumental mass fractionation effects. Note that the $^{26}Mg/^{24}Mg$ distribution for BG 2-6 is clearly distinct from the distribution for normal samples, whereas the $^{25}Mg/^{24}Mg$ distributions overlap completely. Each entry in the histograms represents the mean of ten sequentially measured ratios.*

of several individual, well defined mineral phases. For BG 2-13 we obtained mineral separates including anorthite. One of the BG 2-13 samples analyzed included Na, Al rich phases which are clearly late alteration products. This sample falls off the line defined by the other BG 2-13 samples. There exists abundant evidence from isotopic studies for recent element redistribution and alteration in Allende (Gray *et al*. 1973; Tatsumoto *et al*. 1976; Chen and Tilton 1976). A major consideration throughout our experiments has been the development of microtechniques for sampling and separating well defined mineral phases and for excluding alteration products from the samples analyzed. Sample WA represents a large, coarse grained inclusion, provided kindly by Chen and Tilton, from which four distinct phases were isolated including, melilite and anorthite. For this inclusion, in particular, the $^{27}Al/^{24}Mg$ of the dissolved samples agrees well with electron-microprobe analyses of the pure mineral phases; therefore, the variation of $^{27}Al/^{24}Mg$ in the analyzed samples and especially the relatively radiogenic Mg in the melilite, is not due to varying admixtures of anorthite (See Fig. 3a).

We note that for three Allende inclusions:

a) Mg anomalies are demonstrably due to ^{26}Mg excess whereas $^{25}Mg/^{24}Mg$ is normal;

b) ^{26}Mg anomalies correlate with $^{27}Al/^{24}Mg$;

c) Large effects are obtained for high purity Al rich minerals (anorthite) which tend to exclude Mg from their structure, and which appear texturally to have formed by recrystallization of the host inclusion;

d) no intercepts significantly below $(^{26}Mg/^{24}Mg)_{\oplus}$ are found.

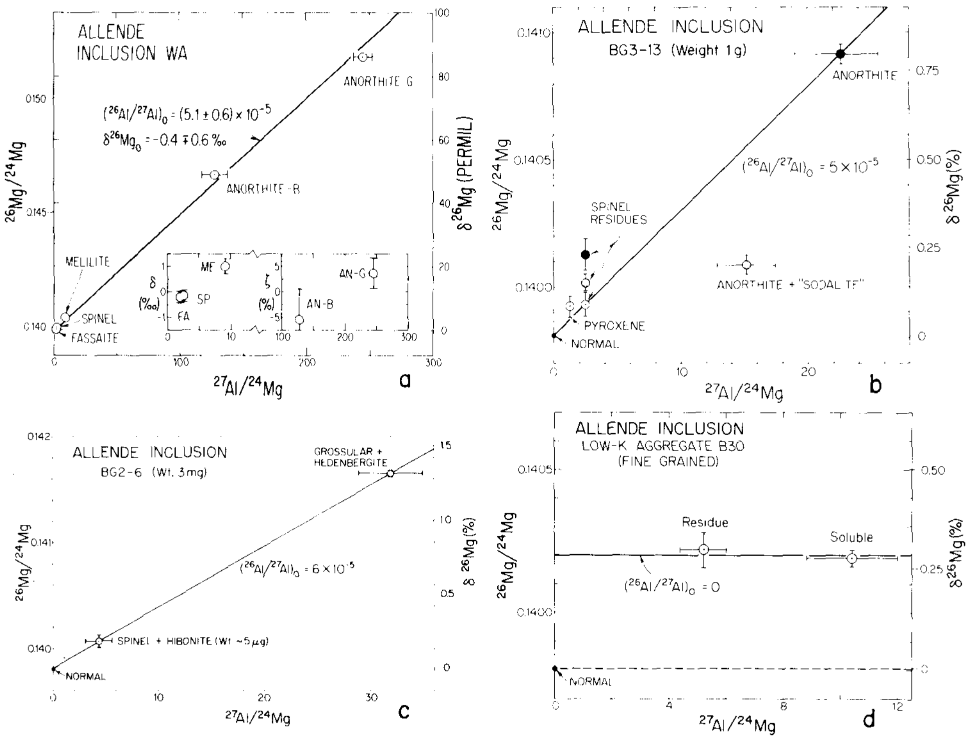

Figure 3. *^{26}Al-^{26}Mg isochrons for Allende inclusions. Note large $^{26}Mg/^{24}Mg$ enrichments for phases from three inclusions (Fig. 3a,b,c). These three inclusions also yield a surprisingly constant $^{26}Al/^{27}Al \sim 5 \times 10^{-5}$. The fourth inclusion (B-30) must have formed after ^{26}Al decayed, but from a reservoir with enriched $^{26}Mg/^{24}Mg$. Detailed discussion of the data can be found in Lee et al. (1976a, 1977).*

For these reasons we believe that the data demonstrate that ^{26}Al was present in these inclusions when they crystallized, and with a ratio $(^{26}Al/^{27}Al)_0 \approx 5 \times 10^{-5}$. The Al-Mg data do not support the incorporation in the solar system of interstellar grains which contained fossil $^{26}Mg^*$. The data on the fourth inclusion in Fig. 3d (sample B-30, a fine grained aggregate from Allende) indicate reheating or formation of this inclusion after ^{26}Al had decayed; the high $(^{26}Mg/^{24}Mg)_0$ indicates that the inclusion incorporated Mg from a high Al/Mg reservoir or, preferably that the inclusion reached isotopic equilibrium as a closed system after the decay of ^{26}Al.

We now briefly consider the implications of the data. As reviewed earlier at this conference by R. N. Clayton, isotopic effects for oxygen have been discovered in a variety of objects including the Allende meteorite (Clayton, Grossman and Mayeda 1973; Clayton, Onuma, Grossman and Mayeda 1976). These effects have been interpreted as due to admixture of an ^{16}O-rich component. For Allende inclusions, the preservation of up to 5% isotopic differences for coexisting phases in an inclusion has indicated the presence of presolar carrier grains which did not reach isotopic equilibrium within the phases in each inclusion. The ^{26}Al-^{26}Mg isochron data imply that isotopic equilibrium was at least ~90% complete. This apparently conflicting evidence can be reconciled if the observed O effects are remnants of nearly complete homogenization of larger initial isotopic effects of ~30% (Wasserburg, Lee and Papanastassiou 1977). The latter authors have also investigated simple models which are compatible with the observed lack of correlation of oxygen and magnesium isotopic anomalies.

The presence of ^{26}Al in the early solar system has the following major implications:

a) It requires late addition of freshly synthesized matter essentially at the time of condensation of at least small (~1 cm) objects.

b) Alternatively it requires production of ^{26}Al without the solar system, presumably by proton reactions on the major elements Mg, Al and Si. In such a case, either only local volumes of the nebula were irradiated, or short range accelerating mechanisms operated in the nebula, or the nebula was continuously mixed.

c) The time scale for condensation of small objects is restricted within a few half-lives or ~3×10^6 years of the ^{26}Al producing event.

d) The addition of ^{26}Al to the solar system within a few million years of condensation of small objects is not consistent with an isolation interval of ~10^8 years for the solar system prior to condensation and formation of planetary objects as calculated from r-process nucleochronologies and assuming that ^{129}I was also produced largely by the r-process (Schramm and Wasserburg 1970). Alternatively ^{129}I was not produced by the r-process, or ^{129}Xe (produced from ^{129}I) started being retained in meteorites ~10^8 years after the time of addition of ^{26}Al and condensation of the refractory elements. If ^{26}Al was produced within the solar system, it is possible that simultaneously produced ^{129}I dominat any r-process contributions. This would invalidate the calculation of a model independent isolation time interval based on ^{129}I and ^{244}Pu (Schramm and Wasserburg 1970; Lee *et al.* 1977).

e) The observed $^{26}Al/^{27}Al$ of 5×10^{-5} will provide an efficient heat source for planetary objects formed within a few million years of the epoch of formation of the Allende inclusions. Schramm *et al.* (1970) have calculated that thermally shielded objects would reach melting temperatures for $^{26}Al/^{27}Al \geq 2 \times 10^{-6}$. The $^{26}Al/^{27}Al$ in Allende inclusions provides enough ^{26}Al to melt even kilometer sized bodies in ~3×10^5 years.

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DISCUSSION

SINGER: You mention the problem of why the effect of proton bombardment is not widespread, i.e., *no* δO^{18} *correlation, etc. The protons in question, of a few MeV, have a very small range and produce only a "skin" effect. Perhaps the proton bombardment you postulate came at a time when most matter was already condensed and agglomerated, and only a small amount was still in the form of small grains, not too far from the Sun. Only the latter would then be appreciably modified by the protons.*

PAPANASTASSIOU: I referred to the difficulty of uniformly irradiating the solar nebula in the presence of the hydrogen gas. I also mentioned that if irradiation of condensed *materials occurred, then, to establish the correlation of* ^{26}Mg *effects with* ^{27}Al*, a remelting of the solid material is needed prior to the decay of* ^{26}Al*, since the target elements for* ^{26}Al *are Mg, Al and Si and not just* ^{27}Al.

ANDERS: It is true that there is no simple 1:1 correlation between Mg^{26} *and* O^{18} *anomalies. Yet it seems significant that all 3 of your samples with positive* Mg^{26} *anomalies have* δO^{18} *of -10 ± 1 permil or so.*

PAPANASTASSIOU: I am not sure of the significance of this observation. There is no obvious correlation because we simply find samples with normal Mg and large oxygen effects. Clearly we need some oxygen measurements for samples which have large ^{26}Mg *anomalies. The problem has been obtaining large enough samples and pure enough mineral separates for these studies. Eventually isotopic analyses for several elements will be possible for the same sample.*