

²⁶Al-²⁶Mg DATING SOLID FORMATION AND PLANETESIMAL ACCRETION AND DIFFERENTIATION IN THE EARLY SOLAR SYSTEM

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Magnesium has three isotopes (24, 25, 26), one of which (²⁶Mg) can be produced by the short-lived decay of ²⁶Al ($t_{1/2} = 0.73$ Myr; mean life = 1.05 Myr). Over 50 years ago, Urey [1] noted that ²⁶Al may have been an important heat source in the young Solar System. Some 20 years later, a series of reports documented the presence of ²⁶Mg excesses (and deficits) in calcium-aluminium-rich inclusions (CAIs), although it was not possible to unequivocally demonstrate that these were due to *in situ* decay of ²⁶Al and not the result of either natural mass fractionation or nucleosynthetic effects.

In 1977, Lee, Papanastassiou and Wasserburg [2] showed using thermal ionization mass spectrometry (TIMS) that excesses of ²⁶Mg in different minerals from an Allende CAI correlated with the Al/Mg ratios of the minerals. This yielded an initial ²⁶Al abundance of $(^{26}\text{Al}/^{27}\text{Al}_0) = (5.1 \pm 0.6) \times 10^{-5}$ in CAIs, which are regarded as the oldest solids that formed in our Solar System. This work had three significant implications: (a) If ²⁶Al was distributed at levels comparable to CAIs throughout the young Solar System, any early formed planetesimals just a few km across would have rapidly melted, (b) It required a young nucleosynthetic event to have taken place in the vicinity of the Solar System shortly before its formation and, (c) It provided the basic framework for the use of the ²⁶Al-²⁶Mg system as a chronometer to date meteoritic material. It is somewhat disconcerting that almost 30 years further on and despite the fact it is possible to measure the $(^{26}\text{Al}/^{27}\text{Al}_0)$ of CAIs with an order of magnitude better precision than [2], no consensus exists on the precise $(^{26}\text{Al}/^{27}\text{Al}_0)$ of CAIs. While the precise $(^{26}\text{Al}/^{27}\text{Al}_0)$ of CAIs has little bearing on the implications (a) and (b) above, it is an important consideration in establishing the age of meteoritic material with respect to CAIs.

Over the following two decades or so, most efforts to use the ²⁶Al-to-²⁶Mg chronometer focused on the application of *in situ* techniques (ion probe) to study CAIs and chondrules in undifferentiated or chondritic meteorites and, to a lesser extent, a search for the former presence of ²⁶Al in differentiated meteorites e.g., see reviews by [3,4]. While ion probe techniques (until recently) are inherently much less precise than TIMS and more recently applied multiple-collector inductively coupled plasma mass spectrometry (MC-ICPMS) techniques, they have the great advantage of being able to non-destructively analyse very small regions of high Al/Mg material (e.g., glass or feldspar) within chondrules and CAIs in chondrites.

These studies have shown that most CAIs from a range of chondrites contained live ²⁶Al at their time of formation with a so-called canonical abundance of ca. 4.5×10^{-5} , although some CAIs record no evidence for live ²⁶Al. Ion probe studies of chondrules from unequilibrated chondrites have generally shown that their initial $(^{26}\text{Al}/^{27}\text{Al}_0) \sim 1 \times 10^{-5}$, implying chondrule formation began ca. 1 Myr after the formation of CAIs and persisted for a further 2 Myr or more.

Despite the fact that ²⁶Al was postulated to be the dominant heat source for melting early formed planetesimals, most attempts to find excesses of ²⁶Mg in meteorites from differentiated planetesimals were fruitless. However, Srinivasan et al. [5] reported the presence of ²⁶Mg excesses in plagioclase from the eucrite Piplia Kalan, which yields an apparent age of ca. 4 Myr after CAI formation. However, the poor correlation between Al/Mg and $\delta^{26}\text{Mg}^*$ indicated that this is a minimum age and that the Mg isotope system has experienced some degree of isotopic resetting. Using TIMS techniques, Nyquist et al. [6,7] subsequently demonstrated that ²⁶Mg excesses was present in both the unique eucrite Asuka 881394 and the angrites SAH99555 and D'Orbigny, corresponding to ages of ca. 4-5 Myr after CAI formation.

The advent of MC-ICPMS techniques in the past 10 years or so, has had the potential to revolutionize both the precision and breadth of application of the ²⁶Al-to-²⁶Mg chronometer to meteoritic material. Significant discoveries using MC-ICPMS technology in the past few years have included a highly precise isochron for bulk CAIs from CV chondrites, which apparently defines a $(^{26}\text{Al}/^{27}\text{Al}_0) = 5.85 \times 10^{-5}$ [8], which is somewhat higher than the "canonical" value. This value is consistent with less precise laser ablation MC-ICPMS studies of CAIs [9]. However, reinvestigation of CAIs from Allende has questioned [10] the revision of the Solar System initial ²⁶Mg abundance to this "super-canonical" value. I will present a substantial body of new ²⁶Al-²⁶Mg data for CAIs including that for aliquots of the CAIs studied in [10].

Importantly, the CAI isochron of [8] defined an initial ²⁶Mg abundance for CAIs that is lower than the terrestrial standard by an amount that is broadly consistent with the initial ²⁶Al abundance of CAIs and the Al/Mg ratio of the bulk Solar System. This apparently demonstrates that ²⁶Al was initially present in the material the Earth accreted from at levels broadly similar to that of CAIs.

MC-ICPMS studies of some bulk chondrules have shown that they have initial ^{26}Al values that approach those of CAIs [11,12], leading to the suggestion that at least some chondrule formation was contemporaneous with that of CAIs. However, in the absence of internal isochrons for such chondrules, it cannot be conclusively demonstrated that the initial ^{26}Al values recorded by such chondrules does not simply reflect inheritance of older material (e.g., remelting of CAI-like material during chondrule formation).

Further high-precision Mg isotope studies of basaltic meteorites from differentiated planetesimals [13] identified small excesses in ^{26}Mg (ca. 0.01 to 0.05‰) that can be used to calculate model ages for the timing of planetesimal differentiation. This is based on the increase in $^{27}\text{Al}/^{24}\text{Mg}$ (ca. 2.0) that accompanies the formation of basaltic magmas as compared to the bulk Solar System $^{27}\text{Al}/^{24}\text{Mg} = 0.1$. Samples of basaltic material from the eucrite, angrite and mesosiderite parent bodies have model ages that range from 2.5 to 4.0 Myr after CAI formation. In most cases, high Al/Mg phases like feldspar appear to record younger ages due to slow cooling and/or thermal resetting after extinction of ^{26}Al . However, not all studies [14] have reproduced the small ^{26}Mg excesses reported by [13].

Using thermal modelling, these timescales for planetary melting or differentiation can be used to place constraints on planetary accretion, which can be shown to have occurred in the first million years of the Solar System. Thus ^{26}Al was the most plausible heat source for planetary melting in the young Solar System. These rapid timescales for accretion and differentiation of earliest formed planetesimals are broadly consistent with constraints from other short-lived chronometers like the ^{182}Hf - ^{182}W system.

Most of these Mg isotope studies have been carried out using first-generation MC-ICPMS instruments. Recent analytical advances now make pseudo-high-resolution or true-high-resolution Mg isotopic analysis possible by MC-ICPMS. This enables resolution of potential isobaric interferences like CN^+ or doubly charged Ca, Ti or Cr that might otherwise potentially result in the acquisition of inaccurate data.

A variety of analytical tests using a new-generation MC-ICPMS instrument are shown in Table 1 that demonstrate the potential accuracy and precision now obtainable for the Mg isotope system by MC-ICPMS. Analyses of standards with gravimetrically prepared ^{26}Mg excesses, and synthetic (Aristar) and natural standards (J11 olivine) subjected to ion exchange procedures show that it is possible to measure ^{26}Mg excesses and deficits with an accuracy and precision < 0.005‰. However, care is needed to avoid analytical artefacts that can produce inaccurate data [15].

Using this methodology we have measured Mg isotope ratios to high precision in olivine from four

main group pallasites. These olivines have uniform ^{26}Mg deficits that can be used to calculate a model age for olivine crystallization and diffusive isolation on the pallasite parent body of 1.05 ± 0.12 Myr ($^{26}\text{Al}/^{27}\text{Al}_0 = [2.16 \pm 0.24] \times 10^{-5}$) after formation of calcium-aluminium-rich inclusions. ^{26}Mg deficit dating may open a plethora of high-precision dating opportunities of meteoritic material that formed in the first two million years of the Solar System. For example, it may be possible to precisely date differentiated meteorites with low Al/Mg like ureilites and aubrites, as well tiny fragments of olivine and orthopyroxene crystals from chondrites. Current sensitivities of MC-ICPMS instruments may allow dating of very small amounts of Mg-rich minerals (ca. 50 to 500 μg in size) and, if Mg isotope measurements on new generation TIMS instruments can achieve the type of precision obtainable for Sr isotopes, it may even be possible to reduce sample sizes by a further several orders of magnitude! However, application of ^{26}Mg deficit dating will require careful assessment of: (a) whether ^{26}Al was uniformly distributed and if Mg isotope heterogeneity existed in the young Solar System, (b) the potential cosmogenic effects on the Mg isotope system and, (c) the actual process(es) that the ^{26}Mg deficits might date.

Table 1 $\delta^{26}\text{Mg}^*$ - $\delta^{25}\text{Mg}$ data of analytical experiments by high-resolution MC-ICPMS analysis.

Sample	$\delta^{26}\text{Mg}^*$ (‰)	$\delta^{25}\text{Mg}$ (‰)	n
Aristar $\delta^{26}\text{Mg}^* 0.01\text{‰}^1$	+0.0107±0.0052	-0.04±0.10	8
Aristar $\delta^{26}\text{Mg}^* 0.03\text{‰}^1$	+0.0311±0.0069	-0.05±0.15	5
Aristar Mg anion-processed ¹	-0.0002±0.0062	-0.03±0.17	6
Aristar Mg cation-processed ¹	-0.0019±0.0049	-0.03±0.04	10
J11 anion-processed ²	+0.0022±0.0040	-0.11±0.06	24
J11 cation-processed ²	+0.0007±0.0053	-0.16±0.05	9
Main group pallasites ³	-0.0155±0.0017		66

¹measured vs pure Aristar Mg, ²measured vs DSM-3, ³measured vs J11 olivine (anion-processed)

References:

- [1] Urey H.C. (1955) *PNAS* 41, 127-144.
- [2] Lee T. et al. (1977) *ApJ* 211, L107-110.
- [3] MacPherson G. et al. (1995) *Meteoritics* 30, 365-386.
- [4] McKeegan K.D. & Davis A.M. (2003) *Treatise of Geochemistry vol. 1*, 431-460.
- [5] Srinivasan G. et al. (1999) *Science* 284, 1348-1350.
- [6] Nyquist L. et al. (2003) *EPSL* 214, 11-25.
- [7] Nyquist L. et al. (2003) *LPS XXXIV*, Abstract #1338.
- [8] Thrane K. et al. (2006) *ApJ* 646, L159-L162.
- [9] Young E.D. et al. (2005) *Science* 308, 223-227.
- [10] Jacobson B. et al. (2007) *LPS XXXVIII*, Abstract #1491.
- [11] Galy A. et al. (2000) *Science* 290, 1751-1753.
- [12] Bizzarro M. et al. (2004) *Nature* 431, 275-278.
- [13] Bizzarro M. et al. (2005) *ApJ* 632, L41-44.
- [14] Wiechert U. & Halliday A. N. (2007) *EPSL* 256, 360-371.
- [15] Schiller M. et al. (2007) *this conference*.