Extreme oxygen isotope ratios in the early solar system

Un réservoir d’oxygène de composition isotopique extrême dans le système solaire primitif

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Résumé : Des grains de silice présentant des enrichissements en oxygène lourd ont été découverts dans la matière organique insoluble de la météorite de Murchison par imagerie isotopique à la microsonde ionique IMS1270 du CRPG de Nancy. Les rapports $^{17}\text{O}/^{16}\text{O}$ et $^{18}\text{O}/^{16}\text{O}$ mesurés dans ces grains sont parmi les plus élevés observés dans la galaxie ($^{17}\text{O}/^{16}\text{O} \geq 0.077$ et $^{18}\text{O}/^{16}\text{O} \geq 0.12$). Une première explication à ces données est une contamination massive (environ 1 ppm) de la nébuleuse proto-solaire par les produits d’une nucléosynthèse stellaire atypique. Une seconde hypothèse est la production in situ par irradiation d’un réservoir d’oxygène exotique. Les calculs de productions d’isotopes d’oxygène par irradiation effectués au CSNSM montrent qu’il est possible à partir d’un gaz de composition solaire de produire un réservoir d’oxygène de composition isotopique compatible avec les données. La condensation de ce réservoir a pu avoir lieu dans les jets bipolaires riches en SiO couramment observés dans les étoiles jeunes de type solaire.

Introduction
Secondary Ion Mass Spectrometry is a powerful tool to find micron-sized exotic isotopic mineral phases in situ in extraterrestrial matter. In 2004 during the ion imaging study of acid insoluble organic matter (IOM) isolated from the Murchison meteorite, J. Aleon discovered grains with a super-heavy oxygen isotopic composition [1]. After systematic oxygen and silicon isotopic mapping using the IMS 1270 ion microprobe at CRPG-Nancy, he found 31 silica-rich grains with extreme $^{17}\text{O}$ and $^{18}\text{O}$ excesses embedded within the IOM (see example in Figure 1). Oxygen isotope ratios in these grains define a mixing line between the solar composition and the most extreme values (see Figure 2). This line could result from mixing, within the ion probe spot, of O from the grains and from IOM in various proportions or from the indigenous isotopic composition of the grains. The mixing occurs between a solar (or close to solar) reservoir and a single and extremely heavy oxygen reservoir (with $^{17}\text{O}/^{16}\text{O} \geq 7.7 \times 10^{-2}$, $^{18}\text{O}/^{16}\text{O} \geq 1.2 \times 10^{-1}$ and $^{18}\text{O}/^{17}\text{O} \leq 1.5$). Silicon isotopic compositions of the grains are indistinguishable from the bulk solar composition. Subsequent isotopic mapping of magnesium isotopes and Al/Mg ratios were done on selected grains by NanoSIMS at Lawrence Livermore National Laboratory to get more insights on their formation and thus on the origin of the oxygen isotope anomalies [2]. All Mg isotopic compositions were found to be solar within error and no $^{26}\text{Mg}$ excess was detected.
Figure 1: Ion images of $^{16}\text{O}$, $^{17}\text{O}$, $^{18}\text{O}$ and $^{28}\text{Si}$ revealing the presence of anomalously $^{17}\text{O}$, $^{18}\text{O}$-rich grains. Scale bars are 2 µm. Intensities are normalised to show comparable variations and increase linearly from dark blue to white. Grains 2, 3, 4 and cluster 6 are silica-rich grains with oxygen isotope anomalies, grain 1 is an Al-rich silicate with solar isotopic composition, grains 5 and 8 are solar corundum grains, grain 7 is a solar chromite and grain 9 is a solar spinel.

An unique stellar source?

Large oxygen isotopic anomalies are usually interpreted as resulting from stellar nucleosynthesis. However, in the case of this new population of particles such an interpretation is facing critical issues. The known population of pre-solar grains exhibits a large range of isotopic compositions reflecting multiple stellar sources and/or stellar condensation locations. Here we are confronted to a mixing of solar-like oxygen with a single highly exotic end-member, indicating a common origin within a well defined nuclear process.

The nucleosynthetic origin of the heavy oxygen isotopes are supposed to be different: $^{17}\text{O}$ is produced by $p$ capture on $^{16}\text{O}$ while $^{18}\text{O}$ results from $\alpha$ capture on the ashes of the CNO cycle ($^{14}\text{N}$) [3]. The association of large $^{17}\text{O}$ and $^{18}\text{O}$ excesses together with a solar Si isotope composition within the same grain represents a challenge to stellar models.

Extreme oxygen isotopic (17/16 and 18/16) ratios reaching 10$^{-1}$ have only been observed once in HR 4049 a post-asymptotic giant branch (AGB) star entering the planetary nebula phase, but no nucleosynthesis model of AGB stars could explain these compositions [4]. Lighter O isotopic compositions have been reported in HD 101013, a Ba star (i.e. an evolved star enriched in products of the s-process nucleosynthesis) [5]. Both HR 4049 and HD 101013 are binaries suggesting a mixing of an extreme O reservoir (observed in HR 4049) with a close to solar O reservoir that could be the companion star [4]. A hypothesis would thus be the seeding of the young solar system by the ejecta of a single star comparable to HR4049 and HD101013. In that respect, we note that, even though AGB stars have already been proposed, via s-process nucleosynthesis, to be a source of excesses in several extinct radionuclide reported in meteoritic materials [6], the Mg isotopic composition of the silica-rich grains shows that these grains were not condensed in an $^{26}\text{Al}$ rich environment ($^{26}\text{Al}/^{27}\text{Al} < 4.8 \times 10^{-4}$).

A single nucleosynthesis process is required to produce both extreme $^{17}\text{O}$ and $^{18}\text{O}$ enrichments in evolved stars such as HR4049, HD101013 and the sources of the silica-rich grains. In the absence of Si isotopic anomalies, this process cannot be explosive H-burning during novae outbursts involving an evolved star and its companion star [7]. The $^{18}\text{O}$ excesses rarely observed in evolved stars have been attributed to the presence in the stellar photosphere of shell He-burning products but require a fine-tuning of the temperature to preclude subsequent conversion of $^{18}\text{O}$ to $^{22}\text{Ne}$. We emphasize that the mixing of the $^{18}\text{O}$-rich shell H-burning reservoir with the $^{17}\text{O}$-rich envelope is expected to produce an O end-member that should exhibit large variations in the $^{18}\text{O}/^{17}\text{O}$ ratio while the present grains are characterized by a constant $^{18}\text{O}/^{17}\text{O} = 1.65 \pm 0.42$ (2σ). We conclude that, although a stellar origin of these particles is possible this hypothesis represent a challenge for stellar nucleosynthesis models and would imply the seeding of the proto-solar nebula at a rather high level (0.1-1 ppm) by nucleosynthetic products of an extremely rare type of star.
Figure 2: Oxygen isotopic composition of anomalous silica-rich grains (black triangles). The oxygen isotopic compositions of the O* reservoir produced by irradiation of the circumsolar gas by particles with characteristics of gradual and impulsive (red dots) solar flares is indicated for spectral indexes $\gamma=2$ and $3$ (green dots) and for $\gamma=3,4$ and $5$ (red dots). The isotopic composition obtained for the main targets elements (N, O, Ne) are reported for the impulsive flare case.

In situ circum-solar gas irradiation? As in the case of extinct radioactivities, an alternative scenario to explain these isotopic anomalies would be their production within the solar system itself. Astronomical observations of Young Stellar Objets (YSO) show that solar-type birthing stars undergo a period of intense X-ray activity during which their circumstellar material can have endured bombardment by light charged particles with as much as $10^5$ times the average fluence observed in the modern Sun. We performed the calculation of the nuclear-induced oxygen reservoir expected by irradiation of a gas of solar composition. Within the MeV energy range, the nuclear production of oxygen atoms is dominated by reactions on the most abundant neighbouring targets N, O and Ne that are in the gas phase. We investigated all reactions leading to $^{16,17,18}$O including channels involving the short periods $^{17}$F ($\tau=64.7$ s), $^{18}$F ($\tau=109.8$ m) and $^{18}$Ne ($\tau=1.67$ s) by bombarding a solar gas target (N, O and Ne in solar proportions) with p, $\alpha$ and $^3$He particles in the E = 3-50 MeV energy range. We assumed a differential power law $dN/dE=K E^{-\gamma}$ spectra, with particles similar to typical contemporary gradual solar flares ($GR: ^3He/\alpha =5 \times 10^{-4}$, $\alpha/p=0.01$, $\gamma=2,3$) and impulsive solar flares ($IM: ^3He/p=\alpha/p=0.1$, $\gamma=3,4,5$) [8, 9] (see Figure 2). In such an approach, the nuclear production of oxygen atoms is dominated by low threshold fusion-evaporation reactions. Experimental cross-sections were used when available and otherwise were calculated using the statistical code EMPIRE II [10] to infer the total cross-section excitation functions. Irradiation by GR type particles fails to explain the data by more than an order of magnitude essentially because $^3$He particles are necessary to produce $^{18}$O/$^{16}$O above $10^{-2}$. With IM type irradiation conditions, we find $^{17}$O/$^{16}$O ranging from 0.25-0.5, $^{18}$O/$^{16}$O from 0.6-1.6, having $^{18}$O/$^{17}$O from 2.4-3.5, depending on the chosen $\gamma$. Reactions products are hereafter noted O*. The main reaction channels contributing to $^{16,17,18}$O* final production are for $^{18}$O* : $^{16}$O($^3$He,p)$^{18}$F($\beta^+$)$^{18}$O* and $^{20}$Ne($^3$He,$\alpha$)$^{18}$F($\beta^+$)$^{18}$O* ; and for $^{17}$O* : $^{14}$N($\alpha,n$)$^{17}$F($\beta^+$)$^{17}$O* ; $^{14}$N($\alpha,p$)$^{17}$O* ; $^{16}$O($^3$He,2p)$^{17}$O* and $^{20}$Ne(p,$\alpha$)$^{17}$F($\beta^+$)$^{17}$O*. The $^{16}$O* is produced by $^{14}$N($^3$He,p)$^{16}$O* ; $^{16}$O(p,p$'$)$^{16}$O* and $^{16}$O($\alpha,\alpha'$)$^{16}$O*. For the two latter reactions, we considered the events in which there is fusion of the incident particle with the target ($^{16}$O) followed by p or $\alpha$ emission, so that the resulting $^{16}$O* will have similar recoil kinematics (energy and angle) as the others O* production channels. The comparison of the theoretical expectations to the known cross-section data (mostly on $\gamma$-ray production) shows a global agreement within a factor 2. However, under the irradiation conditions considered (especially for $\gamma \geq 4$), the O* production is dominated by the low energy part of the cross sections, which is less constrained by experimental data, there is thus an order of magnitude uncertainty on the inferred ratios. On figure 2, we report the isotopic composition of the three main target elements (N, O, and Ne) together with the global GR and IM results. The irradiation of a solar gas by particles with characteristics of impulsive solar flares (IM)
provides a nuclear-induced O* reservoir with both $^{17}\text{O}^{16}\text{O}$ and $^{18}\text{O}^{16}\text{O}$ ratios that is an order of magnitude above the most extreme measured ratios (see figure 2). To prevent a complete dilution of the O* anomaly in the large amounts of free solar oxygen expected to be released in the irradiation zone, it must be isolated from the irradiated gas prior to condensation. Being nuclear-induced, O* is characterized by a high recoil energy ($\sim$ 1 MeV). After leaving the irradiation zone it could be retrieved from the gas phase by a condensation reaction with SiO:

$$\text{SiO}_{(\text{gas})} + \text{O*} \rightarrow \text{SiO}_2(\text{solid})$$

We emphasize that the existence of a selective condensation path is essential to preserve the nuclear-induced isotopic anomaly, should the O* reservoir be mixed with the bulk early solar system oxygen reservoir and the resulting anomaly would be below the detection level ($<10^{-6}$).

Large SiO emission is commonly observed in high velocity protostellar molecular outflows, with inferred SiO abundance up to $10^4$ greater than in quiescent clouds [11]. Such energetic SiO-rich outflows could be the location for the isolation of the energetic O* reservoir and the subsequent condensation of silica-rich micrometer-sized grains. In such a chemical reaction, $^{29,30}\text{Si}$ excesses in SiO$_2$ from nuclear-induced Si* are expected to be negligible because the intermediate species Si*O$_{\text{gas}}$ will be diluted in the major solar SiO$_{\text{gas}}$ reservoir. The observed mixing line can be explained by a mixture of 0.1% to 10% of the inferred O* reservoir with solar SiO.

Open questions

Of crucial importance is the total abundance of these grains in the early solar system. Based on isotopic imaging, their abundance in the Murchison meteorite is estimated to be in the 0.1-1 ppm range. Surprisingly, their search in Orgueil by similar method was unsuccessful leading to an upper limit of 50 ppb. These findings may indicate an heterogeneous distribution of these grains in the proto-solar nebulae and/or a preferential alteration/destruction of these particles by an unknown process in Orgueil. If it turns out that the total abundance of these grains prohibits their production by \textit{in situ} irradiation, the general irradiation-condensation scenario proposed might still be interesting to follow. Indeed, we note that the isotopic anomalies in HR 4049 are observed in the stellar winds and were found in CO$_2$ that could be the trapping reservoir for an anomalous O* via a similar reaction : CO + O* $\rightarrow$ CO$_2$. This surprising similarity may point toward a widespread selective chemical trapping of nucleosynthetic reservoirs occurring in stellar ejecta/outflows that could explain the similarity between the CO$_2$ isotopic composition in HR 4049 and the SiO$_2$-rich grains from Murchison.

References: