Evidence for Nebular Condensation of Sub-micron Refractory Metal Alloys. T. Berg[1,2], E. Marosits[2], J. Maul[1], G. Schönhense[1], P. Hoppe[2], U. Ott[2] and H. Palme[3], [1]Institut für Physik, Staudingerweg 7, D-55128 Mainz, Germany, [2]Max-Planck-Institut für Chemie, Becherweg 27, D-55128 Mainz, Germany, [3]Forschungsinstitut und Naturmuseum Senckenberg, Senckenberganlage 25, D-60325 Frankfurt am Main, Germany.

Introduction: Alloys of refractory metals are expected as first condensates from a cooling nebular gas [1]. Complex particles (tenths of µm) containing the most refractory metals Re, Os, W, Ir, Mo, Ru, Pt and Rh in approximately solar abundances were first reported by [1,2]. These opaque assemblages (OA) were found to be affected by exsolution, oxidation and sulfurization, leading to the redistribution of refractory elements into metal-, sulfide- and oxide-phases [3-5]. Tiny isolated sub-µm refratory metal nuggets (RMN) with compositions compatible with a condensation origin were described by [6] and [7], but only a small number of particles was analyzed.

OA and RMN almost exclusively occur embedded in Ca,Al-rich inclusions (CAIs) that are widely believed to have formed by condensation [8]. More detailed research, however, shows that only few, if any, CAIs are aggregates of pristine nebula condensates. Most have a complex history involving partial melting and secondary alteration [9]. As a consequence not a single mineral grain in these inclusions can be unambiguously identified as a nebular condensate.

Here we report the compositions of 88 sub-µm RMN extracted from an acid resistant residue of the CM chondrite Murchison. Chemistry and morphology strongly suggest that these particles indeed are primary nebular condensates. The striking agreement of the compositions with predictions from condensation calculations allows to estimate maximum cooling rates of the gaseous environment from which the RMN condensed.

Analysis: A large number (458) of RMN was identified by SEM in an acid resistant Murchison residue that was prepared using procedures described in [10]. The predominant fraction of RMN shows a monocrystalline structure (Fig.1). Compositions of 88 arbitrarily chosen particles with sizes between ~90nm and ~650nm were analyzed by energy dispersive X-ray spectroscopy. No correlation between composition and size was observed. Individual compositions were compared with single-phase equilibrium condensation calculations described by [1,11] at a pressure of 10Pa. For each particle the best fit condensation temperature was obtained by minimizing the difference between calculated condensation curves (Fig.2) and measured composition, using simultaneous least squares fitting for 9 metals. In Fig.2 each particle is plotted at its

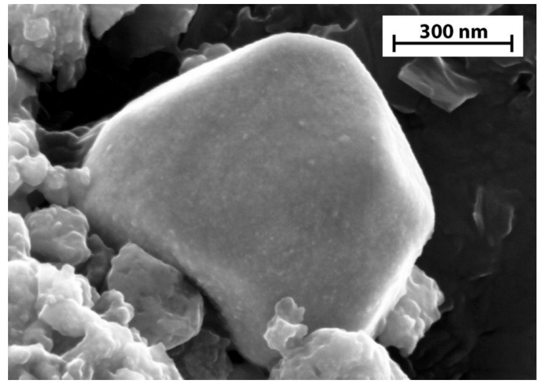

Fig.1 *Exemplary RMN with a composition incompatible with geochemical processes (by weight%: W 5.8, Os, 13.0, Ir 24.0, Mo 14.2, Ru 31.1, Pt 9.6, Ni 1.9, Fe 0.4) and polyhedral surface characteristics indicating a monocrystalline cubic structure.*

calculated equilibration temperature. The excellent fits strongly suggest that the metal grains formed by condensation. Equilibration temperatures of individual particles vary from 1616K to ~1450K at 10Pa. The well defined cut off temperature of 1616K is identical to the perovskite condensation temperature, one of the earliest phases to condense from a cooling solar gas [8]. The observed diversity of equilibration temperatures can be explained by trapping and burial of RMN in simultaneously condensing silicates and oxides [12] which removes the particles from thermodynamic equilibrium with nebular gas. This model assumes that the observed population of RMN is from one or several CAIs.

The rapid compositional changes of our population of RMN allow to estimate maximum cooling rates of the gas from which these particles condensed. Between ~1620K to ~1550K major changes in the composition of RMN occur. Osmium dominated alloys become more and more rich in Mo and Ru and the fractions of Fe and Ni increase slowly. In this range temperature differences of at least 10K at a given pressure can be distinguished by the varying chemical composition of condensing particles (Fig.2). As an example we have calculated the growth of a particle with an initial diameter of 450nm. The calculations are based on the collision frequencies of gaseous Os-, Ru-, and Mo-atoms with the RMN. The minimum time for condensation of these atoms is obtained by

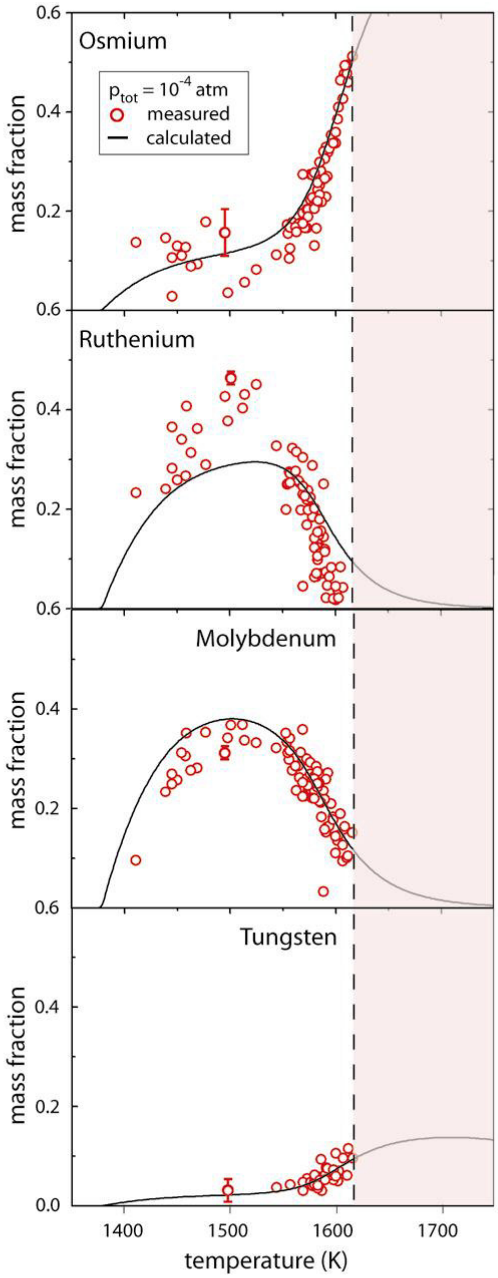

Fig.2 *Striking agreement of theoretical predictions and measured compositions of RMN. Average errors are indicated. RMN with element contents below the detection limit are not plotted.*

assuming that each colliding atom is sticking to the RMN. At a pressure of 10Pa, Os-based growth times within the temperature range of 1620K to 1550K are ~1.5 years/K. Thus a compositional change from 1620K to 1610K requires at least 15 years to accumulate the necessary number of Os atoms. The required time is shorter for Ru and Mo (and considerably more for Fe and Ni), because these elements are more abundant in the gas phase and at the initial stage of condensation fewer Ru- and Mo- atoms are required to achieve the equilibrium composition. The inverse of minimum growth times are maximum cooling rates, which are limited by the results for Os to a value of 0.6 K/year.

Conclusions: Analysis of sub-µm RMN provide, for the first time, direct evidence for condensation in the early solar system. Trapping and burial of RMN in simultaneously condensing silicates and oxides is the most likely process by which these particles were conserved. Comparison with condensation calculations allows to estimate growth rates of RMN. Maximum cooling rates of the parental nebula are on the order of 0.6 K/year, much slower than cooling rates of molten type B CAIs [13]. If, as we have assumed so far, our RMN are from CAIs, it is thus possible for the first time to see through the complex structure of most CAIs and infer the thermal history of CAI components that formed by condensation. This provides severe constraints for the astrophysical environment of CAI formation.

Although RMN were almost exclusively found in CAIs in previous studies [6], we can not exclude that our particles were originally located in the matrix of the meteorite. However, our conclusions are valid irrespective of their original location, and the analyzed particles are among the very first solid objects that formed in the solar nebula. They represent the most pristine solar system material found so far since the monocrystalline structure and the common occurrence of geochemically incompatible elements indicate the absence of secondary alteration.

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