*American Mineralogist, Volume 110, pages 489–500, 2025*

# Rubinite, $Ca_3Ti_2^{3+}Si_3O_{12}$, a new mineral in CV3 carbonaceous chondrites and a refractory garnet from the solar nebula

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## Abstract

Rubinite (IMA 2016-110) is a recently discovered $Ti^{3+}$-dominant refractory mineral in the garnet group from the solar nebula. It has the $Ia\bar{3}d$ garnet-type structure with $a = 12.19(1)$ Å, $Z = 8$, and an end-member formula of $Ca_3Ti_2^{3+}Si_3O_{12}$. Rubinite was identified as micrometer-sized crystals in five refractory Ca,Al-rich inclusions (CAIs) from the CV3 carbonaceous chondrites Allende, Efremovka, and Vigarano. In the Vigarano CAI *V3*, it occurs in the central portion of an ultra-refractory fragment with Zr,Y,Sc-oxide, spinel, and davisite-diopside, all enclosed within an amoeboid olivine aggregate. In the Allende Compact Type A (CTA) CAI *AE01-01*, it occurs with gehlenitic melilite, perovskite, spinel, hibonite, davisite, grossmanite, and diopside. In Efremovka, rubinite occurs within gehlenitic melilite with perovskite, spinel, and grossmanite in three CTA CAIs *E101*, *E105*, and *40E-1* (in a compound CAI). Rubinite is present in spinel-poor regions in all four of the Efremovka and Allende CAIs, but it is in contact with spinel in the Vigarano inclusion.

The mean chemical composition of type rubinite in Allende is (in wt%) CaO 32.68, $Ti_2O_3$ 14.79, $TiO_2$ 13.06, $SiO_2$ 28.37 $Al_2O_3$ 3.82, $Sc_2O_3$ 1.80, $Na_2O$ 1.01, $ZrO_2$, 0.80, MgO 0.79, $V_2O_3$ 0.61, FeO 0.53, $Y_2O_3$ 0.07, $Cr_2O_3$ 0.05, total 98.38, giving rise to an empirical formula of $(Ca_{2.94}Na_{0.08})(Ti^{3+}_{1.04}Ti^{4+}_{0.59}Sc_{0.13}Mg_{0.10}V_{0.04}Fe_{0.04}Zr_{0.03})(Si_{2.38}Al_{0.38}Ti^{4+}_{0.24})O_{12}$, where $Ti^{3+}$ and $Ti^{4+}$ are partitioned based on stoichiometry. Efremovka rubinite has a similar composition with a mean empirical formula of $(Ca_{2.97}Na_{0.06})(Ti^{3+}_{1.05}Ti^{4+}_{0.66}Mg_{0.12}Sc_{0.09}Zr_{0.03}V_{0.03}Y_{0.01}Fe_{0.01})(Si_{2.36}Al_{0.48}Ti^{4+}_{0.16})O_{12}$. Vigarano rubinite is much more Y-, Sc-, and Zr-rich, having an empirical formula of $(Ca_{1.89}Y_{0.83}Mg_{0.28})(Ti^{3+}_{0.59}Sc_{0.50}Zr_{0.72}Mg_{0.2}V_{0.02}Cr_{0.01})(Si_{1.64}Al_{1.18}Ti^{4+}_{0.07}Fe_{0.06})O_{12}$. All rubinites are $Ti^{3+}$-rich, but a significant amount (11–46%) of the Ti is 4+.

In the Efremovka CTAs, spinel is $^{16}$O-rich ($\Delta^{17}O \sim -24‰$); rubinite and perovskite show limited ranges of $\Delta^{17}O$ (from −24 to −16‰; most analyses range from −24 to −20‰); melilite and grossmanite are the most $^{16}$O-depleted minerals ($\Delta^{17}O$ range from ~ −10 to −4‰ and from −8 to −5‰, respectively). In the Allende CTA *AE01-01*, spinel and hibonite are $^{16}$O-rich ($\Delta^{17}O \sim -24‰$); melilite, rubinite, and perovskite show large ranges in $\Delta^{17}O$ (from −23 to −3‰, from −21 to −6‰, and from −14 to −2‰, respectively); grossmanite is uniformly $^{16}$O-depleted ($\Delta^{17}O \sim -3‰$).

Rubinite formed under highly reducing conditions in the solar nebula by gas-solid condensation and crystallization from a Ca-, Al-, and Ti-rich melt. Subsequently, most rubinite grains in the Allende CAI and some in the Efremovka CAIs may have experienced O-isotope exchange to various degrees with an $^{16}$O-depleted ($\Delta^{17}O \sim -2‰$) aqueous fluid on the CV chondrite parent asteroid. However, crystallization from a Ca,Al,Ti-rich melt that recorded O-isotope exchange with nebular gas with variable $\Delta^{17}O$ or post-crystallization O-isotope with such gas cannot be excluded. The mineral name is in honor of Alan E. Rubin (b. 1953), a cosmochemist at the University of California, Los Angeles (UCLA), U.S.A., for his many contributions to research in cosmochemistry and mineralogy of meteorites.

**Keywords:** Rubinite, $Ca_3Ti_2^{3+}Si_3O_{12}$, refractory mineral, Vigarano, Allende, Efremovka, CV carbonaceous chondrites, refractory inclusions, oxygen isotopes, eringaite, garnet