# Coordinated In-Situ Analysis of Meteoritic Nanodiamonds

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## Introduction

**Meteoritic nanodiamonds (NDs)**

- carbon nanograins (2–5 nm) trapped in carbonaceous meteorites thought to be presolar
- carry stellar nucleosynthetic anomalies and encode processes predating the Solar System.

**Challenge**

**Traditional bulk analyses** mask ND subpopulation variation, preventing origin(s) identification.

**Objective**

Differentiate **presolar stardust** vs. **solar system** ND formation in carbonaceous chondrites and returned asteroid samples

## Methods

Sulfur Embed Microtome → **Sample Prep** → 70-100 nm thin section

In-situ aberration corrected STEM/TEM → **Imaging** → EDXS (composition) EELS (bonding)

NanoSIMS → **Isotopic Maps** → C,N Isotopes

## Future Work

Systematically locate ND clusters in carbonaceous chondrites and returned asteroid samples

Determine dist. of C and N isotopes for ND cluster subpopulation formation mechanisms

## References


1. S. J. Desch and N. Miret-Roig, "The Sun's birth environment: Context for meteoritics," Space Sci. Rev., vol. 220, no. 7, Art. no. 76, 2024.
2. G. R. Huss and R. J. Lewis, "Presolar diamond, SiC, and graphite in meteorites," Geochim. Cosmochim. Acta, vol. 60, pp. 331–346, 1996.
3. G. R. Huss, S. T. Husa, and S. A. Sandford, "UV processing of presolar organic ices," Astrophys. J., vol. 849, p. 75, 2017.
4. A. Kouchi et al., "Novel routes for diamond formation in interstellar ices and meteoritic parent bodies," Astrophys. J. Lett., vol. 626, L129, 2005.
5. A. Kumar et al., "Formation of nanodiamonds at near-ambient conditions via microplasma dissociation of ethanol vapour," Nat. Commun., vol. 4, Art. no. 2618, 2013.
6. J. Llorca and I. Casanova, "CO + $H_2$ reaction over Fe–Ni metal at low pressures: Implications for nebular diamond formation," Geochim. Cosmochim. Acta, vol. 64, no. 15, pp. 2673–2684, 2000.
7. L. R. Nittler and F. Ciesla, "Astrophysics with extraterrestrial materials," *Annu. Rev. Astron. Astrophys.*, vol. 54, pp. 53–93, 2016.
8. G. Pareras et al., "Single-atom catalysis in space – II. Ketene–acetaldehyde–ethanol and methane synthesis via Fischer–Tropsch chain growth," Astron. Astrophys., vol. 687, p. A230, 2024.
9. R. M. Stroud et al., "Isotopic and microstructural distributions in circumstellar nanodiamonds: Stellar processes recorded in meteoritic presolar grains," Meteorit. Planet. Sci., vol. 59, pp. 1–28, 2024.


## Current Progress

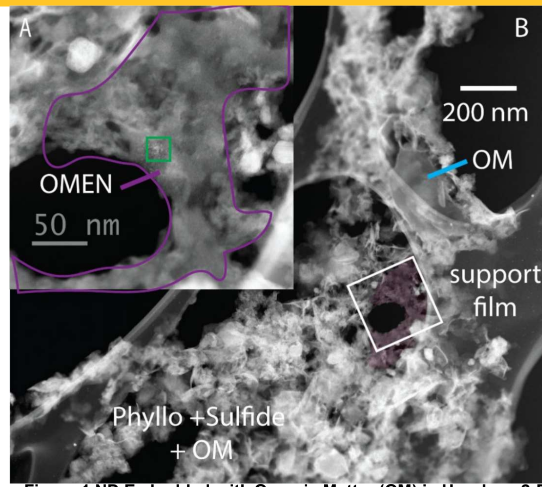


Figure 1 ND Embedded with Organic Matter (OM) in Hayabusa2 Particle(Dark-field STEM)

**Figure 1**
Microtomed Ryugu particle on lacey carbon grid.

(A) Organic matter (OM) with embedded nanodiamonds (OMEN) (magenta)

(B) Petrographic Context of ND cluster in fine grained matrix (phyllosilicates/ sulfides/OM). Elliptical void suggests **NDs form as an interstellar icy particle rind.**

**Figure 2**

**(A)**
EDXS spectra
Amorphous C in **red** is N-richer than ND cluster (gold).

*Cu peak = system artifact; Si/Al/Mg/Fe/O from nanoscale insoluble organic residue.*

**(B)**
EELS spectra
Signature C K-edge
ND ($sp^3$)
amor-OM ($sp^2$)

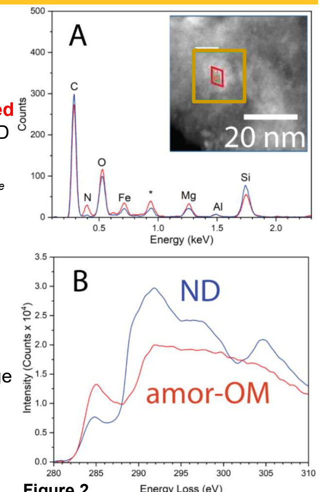


Figure 2

## Formation Mechanisms & Distinct Isotopic Fingerprints

### Cold Formation Mechanisms (T<100K)

*Radical Mediated Nucleation*

**Microplasma Alcohol Vapor Dissociation**

$$(C_2H_5OH)_v \xrightarrow[k_1]{\text{plasma}} n(\text{C-based radicals})\cdot + OH\cdot + H_2$$

Ethanol C-C Bonds are ideal
Atmospheric pressure microplasma
T ≈ 100 °C
Residence time ≈1 ms

**UV Photolysis of Organic-Rich Ices**

$G_0 > 30$

$$H_2O:CO:CH_4\text{ice} + h\nu(<200nm) \xrightarrow[k_1]{UV} [R]\ (CH_3, CH_2\bullet)$$

Organic ice mantles absorb FUV photons
(λ < 200 nm)
H2O-rich ice + minor $CH_4$, $CH_3OH$, CO, $NH_3$
(1-5%)

**Circumstellar Outflow (CTTS at 1 AU)**
Early Solar System active accretion
Lyα Dominated (88%)

| UV Flux | FUV Flux (erg cm⁻² s⁻¹) (912-1700Å) | $G_0$ |
|---|---|---|
| | ~1.6 × 10⁴ | ~10⁷ |

**Outer Nebula**
UV photoevaporation truncates disk at 50–100 AU

| UV Flux | FUV Flux (erg cm⁻² s⁻¹) (912-1700Å) | $G_0$ |
|---|---|---|
| | 0.05-5 | ~30-3000 |

**Diffuse ISM & Cold Molecular Cloud**
UV processing of organic ices

| UV Flux | FUV Flux (erg cm⁻² s⁻¹) (912-1700Å) | $G_0$ |
|---|---|---|
| | 0.05-5 | ~30-3000 |

**Inner Nebula**
Hydrocarbon Catalysis on Fe-Ni grains under solar nebula conditions

| UV Flux | FUV Flux (erg cm⁻² s⁻¹) (912-1700Å) | $G_0$ |
|---|---|---|
| | ~1.6 × 10⁴ | ~10⁷ |

**Formation ⇌ Isotopic Signature ⇌ Origin**

| δ¹³C (‰) | | δ¹⁵N (‰) | | Viable Environment |
|---|---|---|---|---|
| Depleted | Enrich | Depleted | Enrich | |
| ✓ | | ✓ | | Circumstellar outflow |
| | ✓ | | ✓ | Diffuse ISM Cold Molecular Cloud |
| ✓ | | ✓ | | Outer Nebula |
| ✓ | | ✓ | | Inner Nebula |

### Hot Formation Mechanisms (T>1000K)

*HT/HP Processes*

**Vapor Condensation from Supernovae Ejecta**

**Precursor Flash Heating/Collisional Shock**

$$C_{org} \xrightarrow[k_1]{\text{flash heating/shock}} C\ (v)$$

**Carbon Vapor Supersaturation**

$$C\ (v) \xrightarrow[k_2]{\text{supersaturation}} [C_n]^*$$

r-process enriched Carbon vapor
**Extreme initial condition (IC)**
(P > 10 GPa)
(T ≫ 1000 K)
Cooling ejecta under low-pressure conditions (<=10^-4 atm) **forms NDs to later enter presolar cloud**

**Fischer-Tropsch Fe-Ni Catalysis**

**M = Fe-NI catalytic site (metal grain surface)**
**Nebular conditions (~300-700K, $10^{-4}$ atm)**

**CO adsorption and activation**

$$CO(g) + M \overset{k_1}{\rightarrow} M - C + M - O$$

**$H_2$ activation**

$$H_2(ads) + 2M \overset{k_H}{\rightarrow} 2M - H$$

**$CH_2$ initiation**

$$M - C + 2M - H \overset{k_\alpha}{\rightarrow} M - CH_2 + M$$

**Carbene insertion**

$$M - CH_2 + CO(g) + M - H \overset{k_{ins}}{\rightarrow} M - C_2H_4 + M - O$$

**Chain growth**
**repeat $CH_2$ initiation + Carbene insertion**
**build $M - C_nH_{2n}$**