

THE ASTROCHEMICAL AND PLANETARY MATERIALS IRRADIATION EXPERIMENT (ASPIRE) at TRIUMF; C. Charles^{1,2,3}, H. Klassen^{1,4}, A. Pearson^{1,5}, B. Haertel⁶, E. Enkelmann⁶, E. Yuan⁷, A. Irving-Hughes⁷, I. Cooke⁷, S. Beale^{1,3}, R.L. Flemming², P.J.A. McCausland², F. Ames¹, N.J.T. Smith¹, O. Kester¹. ¹TRIUMF (4004 Wesbrook Mall, Vancouver, BC, Canada, V6T2A3, ccharles@triumf.ca), ²Dept. of Earth Sciences, Univ. of Western Ontario (1151 Richmond St. N., London, ON, Canada, N6A5B7), ³Dept. of Chemistry, Simon Fraser University (8888 University Drive, Burnaby, BC, Canada, V5A1S6), ⁴Dept. of Physics, Univ. of Toronto (60 St. George Street, Toronto, ON, Canada, M5S1A7), ⁵Dept. of Physics & Astronomy, Univ. of Waterloo (200 University Ave W, Waterloo, ON, Canada, N2L3G1), ⁶Dept. of Earth, Energy, and Environment, Univ. of Calgary (2500 University Dr. NW, Calgary, AB, Canada, T2N1N4), ⁷Dept. of Chemistry, Univ. of British Columbia (2036 Main Mall, Vancouver, BC, Canada, V6T1Z1). [56th Lunar and Planetary Science Conference (LPSC), Woodlands, TX, 2025. Abstract #2098].

Introduction: ASPIRE – the *AS*trochemical and *PL*anetary materials *IR*radiation *E*xperiment is a newly commissioned experimental setup at TRIUMF – Canada’s particle accelerator centre. ASPIRE enables irradiations of diverse planetary (geologic, meteoritic) and astrochemical materials with accelerated isotope beams spanning the chart of the nuclides, for novel non-traditional accelerator-based research across fields. Solids, liquids, and gases of nearly all types can be bombarded with high-energy particle beams to simulate radiation-induced sample effects in unique settings including planetary (i.e. deep subsurface), Solar System and early protoplanetary disk (PPD), or interstellar and nebular environments. Samples may include geologic minerals, cryogenic materials / phases especially ices, hypersaline brines, molten phases, artificial materials, electronics, and biological or biogeochemical media.

Irradiations and Optics: Fig. 1 shows that ASPIRE irradiates samples with accelerated beams created at TRIUMF’s ISAC (Isotope Separator and ACcelerator) complex [1]. Stable non-radioactive ion beams of nearly all isotopes are generated at the OLIS (Off-Line Ion Sources) facility [2] consisting of a surface, microwave, and ECR ion source (“Supernanogan” from PANTECHNIK). Rare radioactive ion beams (RIBs) may be used for irradiations, produced by the Isotope Separation On-Line (ISOL) method [3] via TRIUMF’s primary 500 MeV p+ driver beam. Beams are then accelerated to ASPIRE (Fig. 1) where an energy on-sample of 1.5 MeV/u for most isotopes below uranium is possible at ISAC-I where ASPIRE is presently installed. Stable OLIS beams of normal abundance or enriched isotopes may be used to irradiate samples.

Future projects requiring higher energies up to 16.5 MeV/u for $A/q=2$ are possible by moving the setup to ISAC-II (Fig. 1). The nominal beam spot-size at ISAC-I downstream from the drift-tube linac is $d \sim 10$ mm at the surface of samples in Fig. 1 where $>10^{12}$ particles-per-second (pps) maximum rate is possible depending on the isotope and charge-state. ISAC-II spot-sizes can be more tightly focused ($d < 1$ mm) at lower pps rates.

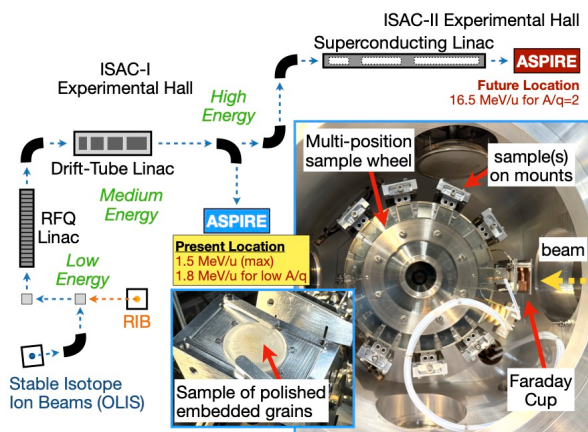


Figure 1: ASPIRE at the TRIUMF accelerator complex showing its location at ISAC-I and (future) ISAC-II. The irradiation chamber as shown is configured with a sample wheel but can accommodate any type of sample configuration. Shown is one example of an irradiated solid (dozens of μm -sized mineral grains per mount).

Construction and Control: The ASPIRE irradiation vacuum chamber (Fig. 1) is fully customizable to accommodate unique and complex irradiation requirements or geometries of solids, liquids, gases, or composite samples, including samples to be held at molten or cryogenic conditions in-vacuum (i.e. layered ice formation) during beam irradiation. Fig. 1 shows a simple “proof-of-principle” configuration for solid μm -sized polished-sectioned grains on a $d \sim 1$ inch epoxy puck (see: *Current Projects*). An upcoming ion desorption probe quadrupole mass spectrometer (QMS) upgrade will provide real-time in-situ precision chemical characterizations of samples during irradiations. Sensors and diagnostics (with exception of the main isolation valve to the accelerator) including vacuum gauges and solenoid valves, power supplies, temperature sensors, a custom Faraday Cup for beam current measurement, stepper motors, and low-light cameras to image samples during irradiations are interfaced, controlled, monitored, and logged by a custom Raspberry-Pi EPICS (*Experimental Physics*

Industrial Control System) hardware interface across a high-speed private LAN and Windows PC GUI.

Ongoing Projects: The world-class availability and diversity of isotope beams at TRIUMF offers ASPIRE the unique opportunity to tackle difficult, novel, and groundbreaking interdisciplinary problems spanning astro-, cosmo-, and geo-chemistry with accelerators. Recent research areas include: (1) fission-track age-dating applications to tectonics, (2) damage and element partitioning studies of irradiated geologic minerals, (3) cosmic ray interactions with interstellar ices and dust, (4) chemical and isotopic variations in PPD solids, and (5) water radiolysis with implications to organic molecule creation and the formation of life.

Fission-Track Thermochronology: Batches of um-sized apatite minerals from rocks spanning Western Canada were irradiated at ASPIRE with accelerated heavy $^{84}\text{Kr}^{+15}$ at 1 MeV/u during the first two beamtimes (Aug and Oct 2024) to induce damage tracks penetrating the mineral surfaces. After acid etching, ion tracks that intersect with pre-existing fission tracks within the apatite (from natural uranium decay) were made visible. Measuring the lengths of these fission tracks, combined with numerical modeling of the fission-track ages (measured separately) is providing a quantitative understanding of the thermal evolution of the apatite grains through time. Interpretation in the regional geology context permits the unravelling of episodes of mountain building, weathering, erosion, burial, and regional faulting processes at high precision.

Beam-Induced Mineral Damage and Element Partitioning Processes: Expanding on the two recent successful ASPIRE beamtimes (*above*), fundamental parameters for beam-induced damage in apatite and other fission-track relevant minerals including zircon, baddelyite, monazite, and titanite remain poorly known. This includes beam energy, irradiation time, beam (mass) purity, and major/minor/trace element content. In-situ QMS analyses of sputtered grains with different chemical compositions combined with high-resolution SEM and EMPA is quantifying fundamental beam-sample interaction conditions to optimize the experimental irradiation of complex natural minerals.

Cosmic Ray Interactions with ISM Ices & Dust: Interstellar Medium (ISM) ices and dust are known to be the birthplaces of molecules. However, molecular compositions of the ice and dust, and how cosmic rays interact with volatile icy mantles to produce ISM molecules are major unanswered questions in astrochemistry. These molecules include those with large knowledge gaps (PAHs, prebiotic molecules, and sulfur-bearing compounds). Irradiation of icy minerals at ASPIRE and QMS quantification of these molecules in real-time and post-irradiation including residues,

offers unique capabilities to test Cosmic Ray models of ISM molecule creation and destruction. In the case of sulfur, ~99% of cosmic S has not yet been detected, with much of this thought to be locked away in dust grains, but its chemical form, location (whether in ices) and interactions with the icy mantle are unknown. Realtime QMS combined with post-irradiation chemical analyses will enable probing for the first time the chemical environment of the sulfur molecules that are formed upon cosmic ray bombardment of ice-coated sulfur-bearing minerals (e.g., FeS and others) to help answer the puzzle of missing ISM sulfur.

Cosmochemical Meteorite Signatures: Calcium-aluminium-rich inclusions (CAIs) and chondrules are the first and oldest solids in our Solar System, formed in the PPD over 4.5 Gyr ago. However, samples show fractionated isotopic variations in various elements (i.e., [4]). Molten CAI and chondrule analogs are being irradiated at ASPIRE with enriched stable beams in different PPD gas/vapour environments to study the formation of element and isotopic fractionations in the melts. Off-line ICP-MS, TIMS, and NMR can measure potential variations in the isotopic ratios, element abundances, and coordination environments. This aims to better quantify (i) gas settings around the melts during their formation, and (ii) sputtered irradiation products to understand how variations may arise. Isotopic and elemental variations in CAIs and chondrules are among the most contentious topics in meteoritics.

Radiolysis of Water & Emergence of Life: Water samples can be irradiated at ASPIRE that mimic the inorganic composition of the world's oldest known water (~2 Gyr old, found at -7850 ft inside Kidd Creek Mine in Timmins, ON) [5] with high-energy α -particles at ISAC-II energies. In minutes this simulates billions of years of natural irradiation from U and Th decay from the surrounding host rock. Off-line chemical and isotopic analyses of these mock water samples may help unravel the possibility of forming organic compounds by radiolytic reactions inside planetary bodies like Earth, Mars, Enceladus, Europa, or exoplanets. This research is particularly timely with the launch of the Europa Clipper mission [6].

Acknowledgments: TRIUMF staff including B. Minato, M. Lovera, M. Vogel, P. Jensen, R. Mendoza, E. Dalla-Valle, and D. Orth greatly assisted with the technical construction and commissioning of ASPIRE.

References: [1] Dilling, J., et al. (eds) (2014). *Springer* ISBN 978-94-007-7962-4. [2] Jayamanna, K. (2013). In: Dilling, J., et al. (eds). *Springer* ISBN 978-94-007-7962-4. [3] Gottberg, A. (2016). *Nuc. Instr. Meth. Phys. Res. B* 376, 8-15. [4] Ebert, S., et al. (2024). *ApJ* 966, 1-8. [5] Warr et al. (2018). *GCA* 222, 340-362, [6] <https://science.nasa.gov/mission/europa-clipper/>.