**Notification No: 598/2026**

**Date of Award: 16-04-2026**

**Name of the scholar:** Sameer Ahmad Mir

**Name of the supervisor:** Prof. Saeed Uddin

**Name of the Department/Center:** Department of Physics, JMI

**Topic of Research:** Hadron Production in Limited and Full Phase Spaces and Properties of Strongly Interacting Matter Produced in Ultra-Relativistic Nucleus-Nucleus Collisions

## Findings

This thesis presents a unified statistical-thermal study of hadron production in ultra-relativistic nuclear collisions, connecting chemical freeze-out, finite baryon-size effects, strangeness imbalance, and kinetic freeze-out through $\phi$-meson transverse-momentum spectra. Its central finding is that an ideal point-particle HRG description is insufficient for a precise description of hadron-yield systematics: finite baryon/antibaryon hard-core repulsion must be included to suppress baryonic densities, improve baryon-to-meson ratios, and obtain a more realistic chemical freeze-out curve. The analysis shows that baryonic chemical potential ($\mu_B$) decreases rapidly with increasing center-of-mass collision energy ($\sqrt{s_{NN}}$), while the freeze-out temperature saturates near the QCD crossover region, indicating the approach to nearly baryon-symmetric matter at RHIC/LHC energies.

A major result is the evidence for sequential chemical freeze-out. Baryons, antibaryons, hyperons, and the $\phi$-meson freeze out earlier than lighter mesons such as pions and kaons. The thermodynamically consistent excluded-volume HRG formulation strengthens this conclusion by using shifted effective chemical potentials and self-consistent densities, with the preferred baryon hard-core radius around ($r_B \sim 0.59$) fm in the consistent model. The thesis also finds that strange-to-nonstrange ratios cannot be described satisfactorily by equilibrium HRG alone. An energydependent phenomenological strangeness-imbalance factor ($\gamma_S$) is required, especially for (K/π), (Ξ/π), and ($\phi$/K) observables. This points toward flavour-dependent freeze-out or residual chemical non-equilibrium in the hadronic stage.

The final part of the work uses $\phi$-meson $p_T$-spectra in (p+p), (p+A), and (A+A) collisions to probe early kinetic freeze-out. Because the $\phi$-meson has hidden strangeness and a small hadronic rescattering cross-section, it carries relatively clean information about the early collective flow field. The extracted transverse-flow and profile parameters support a sequential freeze-out picture in which chemical composition is fixed first, while momentum spectra retain information about later collective expansion. Overall, the thesis builds a coherent phenomenological bridge from limited experimental hadron yields to full freeze-out systematics, showing that finite-size repulsion, thermodynamic consistency, strangeness non-equilibrium, and $\phi$-meson spectra are all necessary for a controlled description of late-stage strongly interacting matter.