

Clustered Nature of Hot and Dense Nuclear Matter: Signatures from Heavy-Ion Collisions

Rui Wang^{1,2,3,*,**} Zhen Zhang^{4,†} Yu-Gang Ma^{1,5,6,‡} Lie-Wen Chen^{1,7,§} Che Ming Ko^{8,||} and Kai-Jia Sun^{1,5,¶}

¹Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), and Institute of Modern Physics, Fudan University, Shanghai 200433, China

²Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

³Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Catania, I-95123 Catania, Italy

⁴Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-Sen University, Zhuhai 519082, China

⁵Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China

⁶School of Physics, East China Normal University, Shanghai 200241, China

⁷State Key Laboratory of Dark Matter Physics, Key Laboratory for Particle Astrophysics and Cosmology (MOE), and Shanghai Key Laboratory for Particle Physics and Cosmology, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

⁸Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA



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Although light nuclear clusters are known to form abundantly in warm and dilute nuclear matter, their role in hot and dense nuclear matter remains unclear due to the lack of experimental indication for their modifications by the Mott effect under such conditions. To address this issue, we resort to intermediate-energy heavy-ion collisions, where light clusters are mainly produced in the transiently formed hot and dense matter. A kinetic approach, which includes dynamically the formation and dissociation of light clusters, is employed to deduce the strength of the Mott effect and the α -particle fraction in hot and dense nuclear matter from the light-nuclei yields measured by the FOPI Collaboration in central Au + Au collisions at energies of 0.25A to 0.6A GeV. We find an unexpectedly abundant α clustering in this environment, which will have profound implications for modeling the nuclear equation of state and describing supernovae and neutron star mergers.

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Introduction—It is generally thought that dense nuclear matter can be regarded almost as a uniform liquid composed solely of nucleons. Such an assumption is based on the belief that the Mott effect [1], which originates from the Pauli blocking of nucleons in the phase space, weakens the attractive correlations among nucleons that lead to bound-state formation [2–4]. These in-medium effects on light clusters are of crucial importance in determining the composition and thermodynamic properties of nuclear matter [5–8]. Although the influence of the Mott effect generally

decreases with increasing temperature, as shown in studies based on the solution of the in-medium Schrödinger equation [4,9], experimental indications are still lacking on the extent to which light-cluster formation and their abundances are modified in hot and dense nuclear matter.

Empirical analyses based on heavy-ion collisions around the Fermi energy [10], where light clusters freeze out at rather low densities, have already allowed the determination of in-medium properties of light clusters in warm and dilute nuclear matter [11–14]. For clusters in hot and dense nuclear matter where their properties remain unexplored, one needs to resort to heavy-ion collisions beyond the Fermi energy and up to the intermediate energy in the GeV regime, where the produced nuclear matter can reach (locally) a temperature as high as a few tens of MeV and a density 2 to 3 times that of the nuclear saturation density ($\rho_0 \approx 0.16 \text{ fm}^{-3}$) [15–17]. Light clusters produced in these collisions may therefore freeze out at much higher densities than those in collisions around the Fermi energy. Since light nuclei are abundantly produced in these collisions [18–20], their expected suppression in hot and dense nuclear matter may not be as large as usually expected. A quantitative study of this reduced in-medium suppression of light clusters, particularly the possible large α -particle abundance, will have great implications for understanding

*Contact author: rui.wang@lns.infn.it

†Contact author: zhangzh275@mail.sysu.edu.cn

‡Contact author: mayugang@fudan.edu.cn

§Contact author: lwchen@sjtu.edu.cn

||Contact author: ko@comp.tamu.edu

¶Contact author: kjsun@fudan.edu.cn

**Present address: INFN, Laboratori Nazionali del Sud, I-95123 Catania, Italy.

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the equation of state of hot and dense nuclear matter [21,22], as well as the physics of supernovae [21–23] and binary neutron star mergers [24], where the nuclear matter can reach similar temperatures and densities [22,25].

For intermediate-energy heavy-ion collisions, where only local—rather than global [26–28]—equilibrium may be reached, a proper description of light-nuclei production requires dynamical approaches that include light clusters up to at least the α particle and the Mott effect, which is only recently realized in Ref. [29]. Here, we employ such an approach to determine the strength of the Mott effect on deuteron (d), triton (t), helium-3 (h), and the α particle from their measured yields in central Au + Au collisions at 0.25A to 0.6A GeV by the FOPI Collaboration [18]. This information then allows for an estimation of light-cluster fractions in nuclear matter at temperatures and densities where light clusters undergo chemical freeze-out in these collisions.

Kinetic approach and Mott effect on light clusters—In the kinetic approach employed in the present study, light clusters, as for nucleons (N), pions (π) and Δ resonances, are included dynamically in the kinetic equations that are derived from the real-time Green's function formalism [30,31]. These kinetic equations, which govern the time evolution of their Wigner functions or phase-space occupations $f_i(\mathbf{r}, \mathbf{p}, t)$, are given as follows:

$$(\partial_t + \nabla_p \epsilon_i \cdot \nabla_r - \nabla_r \epsilon_i \cdot \nabla_p) f_i = I_i^{\text{coll}}[f_n, f_p, f_d, \dots], \quad (1)$$

with i denoting p (proton), n (neutron), d , t , h , and α , as well as the different charged states of π and Δ . In the above equation, $\epsilon_i[f_n, f_p, \dots]$ represents single-particle energies, which can be derived from an energy-density functional. In this study, except for ϵ_π , which includes only the kinetic contribution, ϵ_i of all other particles are obtained from an extended Skyrme interaction [32–35] that reproduces key astrophysical observables such as the mass-radius relation and the tidal deformability of neutron stars. The collision integral I_i^{coll} consists of a gain term ($<$) and a loss term ($>$),

$$I_i^{\text{coll}} = K_i^<[f_n, f_p, \dots](1 \pm f_i) - K_i^>[f_n, f_p, \dots]f_i, \quad (2)$$

where the plus and minus signs are for bosons and fermions, respectively. Both terms contain contributions from various scattering channels, such as $nnnp \leftrightarrow n\alpha$, that can be obtained from diagrammatic expansions of many-body Green's functions [30]. The above kinetic equations can be solved using the test-particle method [36], with the drift term on the left-hand side treated by the lattice Hamiltonian method [37,38], and the collision integral on the right-hand side treated in a stochastic way [30,39,40].

The inclusion of in-medium effects on light clusters is essential for a proper dynamical description of their production in heavy-ion collisions. From the in-medium Schrödinger equation, the binding energy of a light cluster

$E_B(\mathbf{P})$ of center-of-mass momentum $\mathbf{P}$ could vanish, and its constituent nucleons become unbound if the phase-space occupation of nucleons in the nuclear medium around the light cluster is sufficiently large [2,3]. This is mainly due to the Pauli blocking of the constituent nucleons inside the light cluster by the surrounding nuclear medium, which weakens their attractive correlations. A phase-space excluded-volume approach, which captures this key feature of the in-medium Schrödinger equation while requiring significantly less computational effort, has been introduced to account for these in-medium effects in solving the kinetic equations [30]. Specifically, the formation of a light cluster of species ν with mass number A and momentum $\mathbf{P}$ in the nuclear medium is allowed only if the average phase-space occupation of both neutrons and protons around the light cluster is less than a cutoff value F_A^{cut} , i.e.,

$$\langle f_\tau \rangle_\nu(\mathbf{P}) \equiv \int f_\tau^{\text{tot}}(\mathbf{p}) |\tilde{\phi}_{\nu, \mathbf{P}}(\mathbf{p})|^2 \frac{d\mathbf{p}}{(2\pi\hbar)^3} \leq F_A^{\text{cut}}. \quad (3)$$

Here, $\tau = n$ or p , and $|\tilde{\phi}_{\nu, \mathbf{P}}(\mathbf{p})|^2$ denotes the normalized one-body probability distribution of the nucleons inside the light cluster. In Eq. (3), the total nucleon occupation f_τ^{tot} contains contributions from both quasifree nucleons and those bound in light clusters, as generalized in Ref. [41] with respect to the original phase-space excluded-volume approach [29,30,42], where only the former is considered. The parameters F_A^{cut} can be regarded as surrogates for the strength of the Mott effect, with smaller values of F_A^{cut} corresponding to a stronger Mott effect, i.e., making it easier for light clusters to dissolve in nuclear medium.

For describing heavy-ion collisions, the above criterion for light-cluster formation is incorporated into the kinetic approach through the collision integral in Eq. (1), i.e., the formation of light clusters from many-body scatterings is allowed only if Eq. (3) is satisfied. There, the f_τ^{tot} is obtained from the phase-space occupations f_i in Eq. (1) for both quasifree nucleons and light clusters in each spatial lattice and at each time step.

For nuclear matter, Eq. (3) can be used to define the Mott momentum P_ν^{Mott} , above which a light cluster of species ν can exist, since $\langle f_\tau \rangle_\nu(\mathbf{P})$ decreases with increasing $|\mathbf{P}|$ in nuclear matter. Light clusters thus have the following distributions in nuclear matter:

$$f_\nu^{\text{eq}}(\mathbf{P}) = \frac{H(|\mathbf{P}| - P_\nu^{\text{Mott}})}{\exp\left[\frac{\epsilon_\nu(\mathbf{P}) - \mu_\nu}{k_B T}\right] \pm 1}. \quad (4)$$

In the above, the plus (minus) sign is for fermions (bosons), $H(|\mathbf{P}| - P_\nu^{\text{Mott}})$ is the Heaviside step function, and μ_ν is the light-cluster chemical potential, which is related to the proton and neutron chemical potentials μ_p and μ_n by chemical equilibrium conditions. The presence of light clusters modifies the occupation of quasifree nucleons in

nuclear matter $f_{\tau}^{\text{eq}}(\mathbf{p})$ to a form deviating from the Fermi-Dirac distribution. In a nuclear matter of baryon density ρ_B , isospin asymmetry δ , and temperature T , the quantities μ_n , μ_p , P_{ν}^{Mott} in $f_{\tau}^{\text{eq}}(\mathbf{p})$ and $f_{\nu}^{\text{eq}}(\mathbf{P})$ can be determined by solving coupled equations, including Eqs. (3) and (4), as described in Supplemental Material [43] and detailed in Ref. [41].

Through Eq. (3), the Mott effect manifests itself in both nuclear matter and heavy-ion collisions, with its strength characterized by $\mathbf{F}^{\text{cut}} \equiv (F_2^{\text{cut}}, F_3^{\text{cut}}, F_4^{\text{cut}})$. Calibrating $\mathbf{F}^{\text{cut}}$ from the measured light-nuclei yields in heavy-ion collisions based on the kinetic approach allows one to obtain an estimate of the strength of the Mott effect. The preferred $\mathbf{F}^{\text{cut}}$ can then be used to deduce the light-cluster fraction in nuclear matter within the phase-space excluded-volume approach. As a prerequisite, we verified that the analytical $f_{\tau}^{\text{eq}}(\mathbf{p})$ and $f_{\nu}^{\text{eq}}(\mathbf{P})$ are reproduced by the kinetic approach in box calculations (see Supplemental Material).

Bayesian inference of $\mathbf{F}^{\text{cut}}$ from light-nuclei yields—Transport model studies of deuteron and triton production [42] and α -particle production [29] have demonstrated that the Mott effect or the value of $\mathbf{F}^{\text{cut}}$ affects appreciably the light-nuclei yields in intermediate-energy heavy-ion collisions. Here, we calibrate the value of $\mathbf{F}^{\text{cut}}$ using the light-nuclei yields from these collisions through Bayesian inference based on a Gaussian process emulator of the kinetic approach. Specifically, using the SURMISE package for Bayesian inference [44], we obtain the posterior probability distribution $p(\mathbf{F}^{\text{cut}}|\mathcal{N}^{\text{exp}}, \mathcal{K})$ for the $\mathbf{F}^{\text{cut}}$ used in the kinetic approach $\mathcal{K}$, given the experimental light-nuclei yields $\mathcal{N}^{\text{exp}}$ from Au + Au collisions measured by the FOPI Collaboration [18] (see Supplemental Material for numerical details). In particular, only collisions at 0.25A, 0.4A, and 0.6A GeV are considered to minimize the effects of heavy fragments at lower collision energies and the contribution of pion-catalyzed reactions to light-nuclei production (e.g., $\pi NN \leftrightarrow \pi d$ [45–47]) at higher collision energies. This then leads to 12 elements in $\mathcal{N}^{\text{exp}}$, namely the yields of d , t , h , and α for the above three incident energies. At 90% confidence level, the inferred values are $F_2^{\text{cut}} = 0.192_{-0.017}^{+0.037}$ for d , $F_3^{\text{cut}} = 0.248_{-0.021}^{+0.075}$ for t and h , and $F_4^{\text{cut}} = 0.345_{-0.032}^{+0.102}$ for α . Note their differences from those used in Ref. [29], where only the contribution of quasifree nucleons to $f^{\text{tot}}(\mathbf{p})$ in Eq. (3) is considered. With the preferred value for $\mathbf{F}^{\text{cut}} = (0.192, 0.248, 0.345)$, we show in Fig. 1 the light-nuclei yields in central Au + Au collisions at the aforementioned three beam energies calculated using the kinetic approach. To illustrate the sensitivity to the Mott effect, we reduce the preferred $\mathbf{F}^{\text{cut}}$ by about 0.1, either for all F_A^{cut} or only for F_4^{cut} , and show the resulting yields in Fig. 1. Note that varying solely F_4^{cut} alters also the yields of other light nuclei, indicating a correlated sensitivity to the cutoff parameters.

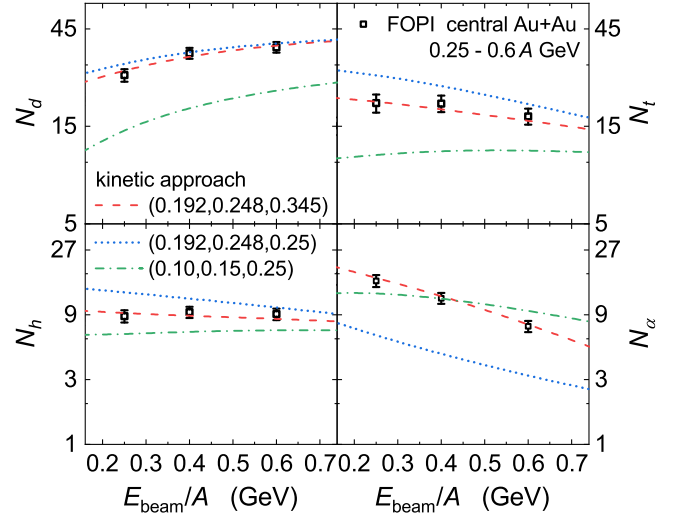


FIG. 1. Light-nuclei yields in central Au + Au collisions at energies of 0.25A to 0.6A GeV from the kinetic approach with the most probable value for $\mathbf{F}^{\text{cut}} = (0.192, 0.248, 0.345)$, and two other values for $\mathbf{F}^{\text{cut}}$. The experimental data are from the FOPI Collaboration [18].

Alpha-particle fraction in hot and dense nuclear matter—Because of the rapid expansion of the nuclear matter formed in heavy-ion collisions, light clusters can freeze out during the early compression stage of the reaction, and carry information about the properties of the hot and dense (locally equilibrated) nuclear medium where they are emitted. The preferred value of $\mathbf{F}^{\text{cut}}$, determined from the final-state light-nuclei yields, provides an estimate of the strength of the Mott effect and can be used to deduce the light-cluster fractions in such matter.

In the upper panel of Fig. 2, we exhibit the distribution of the local baryon density ρ_B associated with the number of chemical freeze-out α particles in heavy-ion collisions, as extracted using the kinetic approach. α particles are seen to mainly freeze out chemically from high-density regions during the most compressed stage of the collisions. This is in contrast to deuterons, tritons, and helium-3 that mainly freeze out from lower densities because of their less enhanced formation rate in dense nuclear matter, which is due to the ρ_N^{A+1} dependence of many-body scatterings employed in the kinetic approach for their production. Therefore, we focus on the α particle and deduce its fraction in hot and dense nuclear matter. Specifically, the chemically freeze-out α -particle number distribution $dN_\alpha/d\rho_B$ is found to peak around $\rho_b = 0.25_{-0.14}^{+0.03}$, $0.28_{-0.14}^{+0.03}$, and $0.32_{-0.17}^{+0.02}$ fm $^{-3}$ for $E_{\text{beam}} = 0.25A$, $0.4A$, and $0.6A$ GeV, respectively, where the lower and upper bounds correspond to the 68.3% probability interval of the distribution.

To avoid ambiguities in determining local temperatures of nuclear matter within the kinetic approach, we extrapolate the chemical freeze-out temperatures determined from the statistical hadronization model used for describing

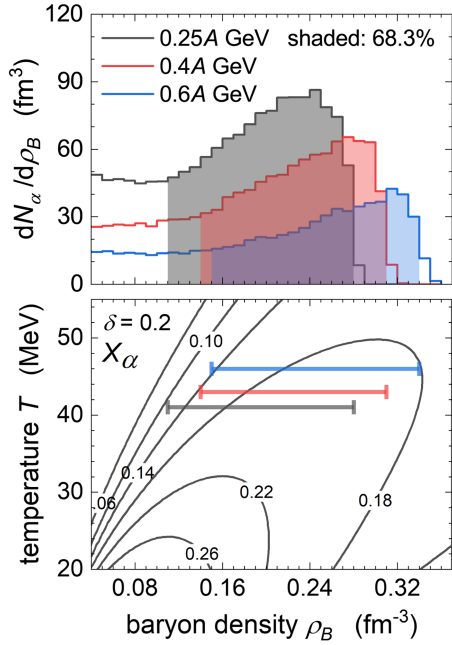


FIG. 2. Upper: freeze-out baryon density distribution $dN_\alpha/d\rho_B$ of α -particle number in central Au + Au collisions at $E_{\text{beam}} = 0.25A, 0.4A$, and $0.6A$ GeV, respectively, obtained from the kinetic approach with the most probable $\mathbf{F}^{\text{cut}}$. Shaded regions indicate 68.3% probability interval. Bottom: contour plot of the α -particle fraction X_α for nuclear matter with isospin asymmetry $\delta = 0.2$ obtained using the phase-space excluded-volume approach with the most probable $\mathbf{F}^{\text{cut}}$. Error bars indicate the densities of the shaded regions in the upper panel.

hadron yields in high-energy nuclear collisions [48] down to intermediate energies. The estimated chemical freeze-out temperatures around which nucleons freeze out in Au + Au collisions at $E_{\text{beam}} = 0.25A, 0.4A$, and $0.6A$ GeV are found to be 41, 43, and 46 MeV, respectively.

With the density ρ_ν of light clusters of certain species obtained by integrating its phase-space distribution in Eq. (4), its fraction in nuclear matter $X_\nu = (A\rho_\nu/\rho_B)$ can be determined. We show in the bottom panel of Fig. 2 the contour plot of the α -particle fraction X_α in nuclear matter with isospin asymmetry $\delta = 0.2$, which roughly corresponds to the isospin asymmetry of the Au + Au collision system, around the aforementioned chemical freeze-out densities and temperatures in the ρ_B - T phase diagram, obtained using the phase-space excluded-volume approach with the most probable $\mathbf{F}^{\text{cut}} = (0.192, 0.248, 0.345)$. The abundant light-nuclei yields observed in intermediate-energy heavy-ion collisions therefore require a surprisingly high α -particle fraction of $X_\alpha \sim 0.2$, indicating a significantly weaker Mott effect, at the chemical freeze-out densities of 0.25 – 0.32 fm^{-3} and temperatures of 41 – 46 MeV. This challenges the conventional picture of hot and dense nuclear matter as a uniform nucleon liquid, and may have crucial implications for the nuclear equation of state, and the physics of supernovae and neutron star mergers.

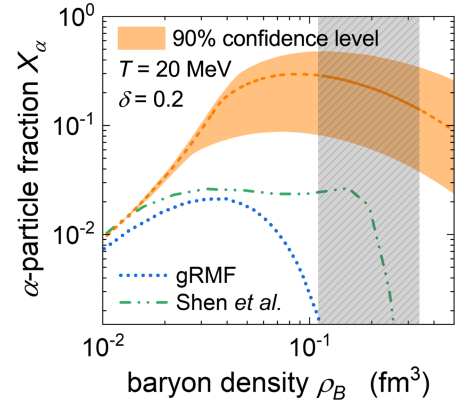


FIG. 3. α -particle fraction X_α together with its uncertainty in nuclear matter at temperature $T = 20$ MeV and isospin asymmetry $\delta = 0.2$ obtained from the phase-space excluded-volume approach with the most probable $\mathbf{F}^{\text{cut}} = (0.192, 0.248, 0.345)$. The results from gRMF, and Shen *et al.* (for $\delta = 0$) [5] are included for comparison. The highlighted area corresponds to the dominant density region where α particles undergo the chemical freeze out shown in Fig. 2.

We compare in Fig. 3 the above results on the α -particle fraction X_α in nuclear matter of $\delta = 0.2$ and at $T = 20$ MeV with those from other approaches. These approaches (their results are available only for $\delta = 0$; note that X_α is generally suppressed in asymmetric matter) include the generalized relativistic mean-field (gRMF) model [5], where the Mott effect is implemented effectively by introducing certain density-dependent (momentum-independent) binding energies of light clusters, and the Thomas-Fermi approximation with the dissolution of α particles realized by an excluded-volume prescription in coordinate space [49] (Shen *et al.*). The orange line represents X_α from the phase-space excluded-volume approach [Eq. (3)] using the most probable $\mathbf{F}^{\text{cut}}$, with its uncertainty obtained by varying F_2^{cut} , F_3^{cut} , and F_4^{cut} within their 90% confidence intervals. The highlighted area corresponds to the dominant density region (combining the regions for the three E_{beam} together), where α particles undergo the chemical freeze-out shown in Fig. 2. It is seen that the X_α at these densities preferred by the light-nuclei yields in intermediate-energy heavy-ion collisions is much larger than that predicted by previous approaches. A much weaker Mott effect on light clusters in hot and dense nuclear matter may need to be introduced in those approaches, probably by introducing explicit momentum-dependent in-medium effects on light clusters, to make their results agree with the light-nuclei yields measured by the FOPI Collaboration. We notice that the in-medium effects on deuterons have already been modified within the generalized relativistic mean-field approach [50] to explain the short-range correlations observed in finite nuclei [51].

Before drawing final conclusions, we note that a more complete treatment of cluster production within the kinetic

approach would require incorporating additional effects, such as the phase-space fluctuations, which are neglected in this Letter. While the Mott effect reduces the importance of fluctuations for cluster production at high densities, a quantitative assessment, obtained by explicitly incorporating fluctuations into the kinetic framework, e.g., via a stochastic way [52], is still required to more accurately evaluate their impact. More generally, at high densities, the strict dilute limit may break down, and multiparticle processes [53] may become relevant. Although the many-body scatterings included here partially account for multiparticle correlations, it is nontrivial to assess to what extent a finite truncation of the collision integral captures all such effects. Detailed studies of these effects are left for future work.

Summary—Based on a kinetic approach that dynamically includes light clusters with mass number $A \leq 4$ and their Mott effect, we are able to study the in-medium effects on light clusters in hot and dense nuclear matter, previously possible only for dilute nuclear matter. From the light-nuclei yields in central Au + Au collisions at intermediate energies measured by the FOPI Collaboration, we have found an unexpectedly abundant α clustering, with a fraction of about 0.2, in hot nuclear matter at densities around 1 to 2 times that of nuclear saturation density. Results from the present analysis indicate a possible clustered nature of hot and dense nuclear matter, suggesting that clustering phenomena may play a more significant role than commonly assumed. They underscore the importance of extending nuclear mean-field models to explicitly include light-cluster degrees of freedom and their Mott effect. These findings also have important implications for various astrophysical phenomena, such as supernovae and binary neutron star mergers, where similar conditions may occur.

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Data availability—The data that support the findings of this article are not publicly available upon publication

because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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