Conference materials
UDC 538.9
DOI: https://doi.org/10.18721/JPM.161.134

Calculation of correlation lengths in 2D Lennard-Jones fluids

I.V. Simkin [1]✉, E.V. Yakovlev [1], N.P. Kryuchkov [1], S.A. Korsakova [1], S.O. Yurchenko [1]

[1] Bauman Moscow State Technical University, Moscow, Russia

✉ vanyasimkin@gmail.com

Abstract. The process of spinodal decomposition in two-dimensional system that was obtained by molecular dynamics simulation has been analysed using the correlation of reciprocal areas of the Voronoi cells. Correlation lengths dependence on the temperature and the critical exponent of the LJ12-6 system in the fluctuation region by the general renormalization group (RG) framework were calculated. We showed the agreement of the calculated critical exponent ν with both experiments and theory. The proposed methodology for correlations of the reciprocal areas of the Voronoi cells is well applicable in the experiments with 2D colloidal systems.

Keywords: soft matter, colloidal particles, tuned self-assembly, phase transitions, molecular dynamics

Funding: I.V.S., E.V.Y., N.P.K., S.A.K and S.O.Y. acknowledge BMSTU State Assignment for infrastructural support. Studies are supported by the Russian Science Foundation, Grant No. 20-12-00356.

Citation: Simkin I.V., Yakovlev E.V., Kryuchkov N.P., Korsakova S.A., Yurchenko S.O., Calculation of correlation lengths in 2D Lennard-Jones fluids, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.1) (2023) 197–204. DOI: https://doi.org/10.18721/JPM.161.134

Материалы конференции
УДК 538.9
DOI: https://doi.org/10.18721/JPM.161.134

Вычисление корреляционных длин в двумерных жидкостях с потенциалом Леннарда-Джонса

И.В. Симкин [1]✉, Е.В. Яковлев [1], Н.П. Крючков [1], С.А. Корсакова [1], С.О. Юрченко [1]

[1] Московский государственный технический университет им. Н.Э. Баумана, г. Москва, Россия

✉ vanyasimkin@gmail.com

Аннотация. Проанализирован процесс спинодального распада в двумерной системе, полученный методом молекулярной динамики с помощью корреляции обратных площадей ячеек Вороного. Рассчитана зависимость корреляционных длин от эффективной температуры системы с потенциалом взаимодействия LJ12-6 в области спинодального распада. Показано соответствие вычисленного критического индекса ν как экспериментальным исследованиям фазовых переходов в двумерных ферромагнетиках, так и теоретическим исследованиям систем Изинга. Предложенный метод корреляций обратных площадей ячеек Вороного может быть применим в экспериментах с двумерными коллоидными системами.

Ключевые слова: мягкая материя, коллоидные частицы, управляемая самосборка, фазовые переходы, метод молекулярной динамики

Финансирование: Работа выполнена при поддержке Гранта РНФ № 20-12-00356 по теме: “Коллективная динамика, упругие и транспортные свойства классических жидкостей в различных режимах межчастичного взаимодействия” на базе МГТУ им. Н.Э. Баумана

Ссылка при цитировании: Симкин И.В., Яковлев Е.В., Крючков Н.П., Корсакова С.А., Юрченко С.О. Вычисление корреляционных длин в двумерных жидкостях с потенциалом Леннарда-Джонса // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.1. С. 197–204. DOI: https://doi.org/10.18721/ JPM.161.134

Introduction

Method for the characterization various phases of matter is one of the central tasks of condensed matter physics and materials science. In particular, the study of the phase transitions in 2D systems has played a crucial role for understanding of the phase transitions and it can be extended to other complex systems. Understanding the process of the phase transitions in 2D systems plays important role in a number of areas, from photonics and electronics [1–8], to novel materials [9, 10],and biophysics [11], since knowledge of the phase behavior opens way to designing systems with the necessary properties.

A great number of phase transitions phenomena studies are carried out by methods of the molecular dynamics (MD) and Monte Carlo (MC) simulation. One of the simplest model which is capable of reproducing gas, liquid, and solid phases behaviour is the Lennard-Jones (LJ) system. Such systems make it possible to study melting and crystallization [12–14], condensation and evaporation [15], spinodal decomposition [16–18].

One of the platforms mimicing molecular behavior are colloidal systems [19–23]. The studies in such systems include crystallization and melting [24–31], reentrant and solid-solid phase transitions [32–34], condensation and critical phenomena [35–37], molecular-like interactions [38, 39], sublimation [40], gelation, slow dynamics in glasses [41–44], the role of three-body interactions of phase transitions [45].

Tunable interactions between colloidal particles can be provided using different physical mechanisms [46]: electrostatic interactions in solvents, [47, 48], tunable interactions induced by external magnetic fields [27, 49], alternating anisotropic and rotating electric fields [50, 51]. Rotating electric fields make it possible to induce and to control interparticle interactions in colloidal systems, and collective dynamics of colloidal particles can be visualized in real time with the spatial resolution of individual particles. In rotating electric fields, interparticle interactions in a colloidal system monolayer are tuned by the following mechanism [51–54]: an external electric field polarizes colloidal particles, that leads to anisotropic interactions; a fast (compared to the particle diffusion time) rotation of the field in the plane of the system makes it possible to achieve isotropic tuned dipole attraction at large distances [51, 54]. The colloidal system in the rotating electric field provides a rich variety of different interactions, including repulsion, attraction, combination of short-range repulsion with long-range attraction, barrier-type interactions with short-range attraction and long-range repulsion, and double-scale repulsive (core–shell) interparticle interactions [55]. This makes it possible to use such system for particle-resolved study of phase transitions [17].

It is required a methodology to study critical phenomena in colloids. The divergence of the correlation length for a mixed phase transition in a 2D colloid model system with nearest neighbor interaction has been shown in Paper [56]. The authors in [57] attempted to calculate the correlation length using the effective interfacial thickness in 2D LJ fluids. In our work, we suggest using the correlation function of reciprocal areas of the Voronoi cells critical temperature vicinity. It allows us to calculate the dependence of the correlation length on the temperature and to determine critical exponent ν in 2D systems.

Materials and Methods

To study the efficiency of density-density correlation method (correlation of reciprocal areas of the Voronoi cells), we performed MD simulations of the system undergoing spinodal decomposition.

We considered system of particles interacting via the potential:

$$\varphi_{12-6}(r) = 4\epsilon\left[\left(\frac{\lambda}{r}\right)^{12} - \left(\frac{\lambda}{r}\right)^{6}\right]. \quad (1)$$

Where $\varphi_{12-6}(r)$ is the usual Lennard–Jones potential (LJ12-6 potential), ϵ and λ are the strength and range of the interaction, respectively. We use the dimensionless temperature $T/\epsilon \to T$, distance $r/\lambda \to r$, surface number density $n\lambda^2/m \to n$, and time

$$t\sqrt{\frac{\epsilon}{m}}\lambda^2 \to t$$

(here, m is the mass of the particle).

To obtain correlation length dependence on the temperature the MD simulations of a system containing $N = 10^4$ particles were performed in an NVT ensemble for different temperatures above the critical. Initially particles were distributed uniformly over the simulation region with periodic boundary conditions. Then at every temperature, it was integrated for 10^6 steps until the equilibrium state was reached. The time step of $\Delta t = 5\times10^{-3}$ was used. The last 10 snapshots of the system were used for correlation lengths calculations with a sampling rate of 5×10^{-3} steps. The cutoff radius was set to $r_c = 5$.

During spinodal decomposition a new state of reduced symmetry emerges continuously from the disordered or symmetric phase as the temperature is reduced. To analyze the fluctuations in the system, it is proposed to use correlation of reciprocal areas of the Voronoi cells $C(r, r')$.

Let us define the correlation function $C(r, r')$:

$$C(r,r') = \left\langle \varphi(r)\varphi(r') \right\rangle. \quad (2)$$

The correlator of the system was calculated as reciprocal areas product of the Voronoi cells of particles at the radius-vector $r - r'$, averaged over each particle $r - r'$. Figure 1 shows the mechanism for calculating the correlator $C(r, r')$. The area of the Voronoi cell $\varphi(r)$ corresponding to the particle at the r' multiplied by the reciprocal area $\varphi(r')$ corresponding to the particle at the $r - r'$.

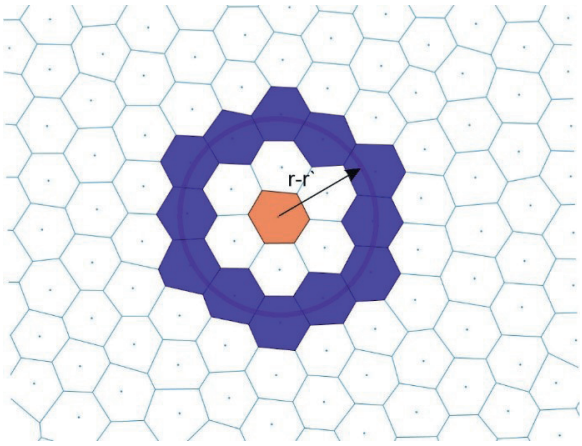

Fig. 1. The field of Voronoi cells for calculating correlator of the system. Voronoi cell corresponding to the particle at the radius vector r is colored orange; Voronoi cells corresponding to the particles at the radius vector $r-r'$ over which averaging is carried out are colored blue

The correlator $C(r, r')$ of the system decreases rapidly with distance above the critical point T_c and nonzero at and below T_c.

In the self-consistent field theory, from the Ginzburg-Landau free energy equation, the correlator $C(r, r')$ of the system is given as follows [58]:

$$C(r) = r^{1-\frac{d}{2}} K_{\frac{d}{2}-1}\left(\frac{r}{\xi}\right), \quad (3)$$

where due to symmetry we can write $C(r)$ instead of $C(r, r')$, ξ is the correlation length, d is the dimension of the system and K_n is the Macdonald function of the n-th order.

Results and Discussion

The correlator (eq. 2) was calculated for the MD system in the vicinity of critical point temperature range. The correlator dependence on the distance and its fit by (eq. 3) are shown in Figure 2.

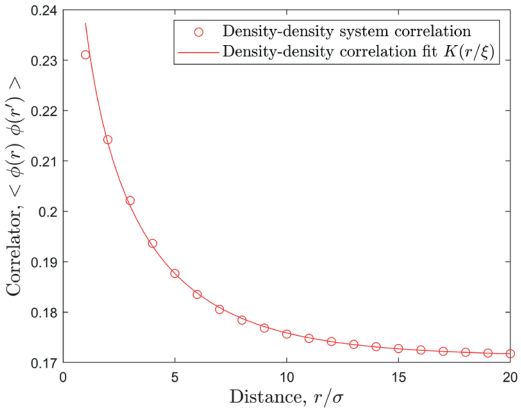

Fig. 2. The correlator dependence on distance of the 2D LJ12-6 system. Red symbols ◦ correspond to calculated correlation, σ is the particle radius. Red solid line is the fit of the calculated correlator (eq. 2) by the equation (3)

From the approximation of the correlator $C(r)$ by the Macdonald function (eq. 3) the correlation length ξ for different temperatures were calculated. Several MD simulation timesteps were considered and Figure 3 shows the average correlation length dependence on reduced temperature $\tau = \dfrac{T - T_{cp}}{T_{cp}}$, where T_{cp} is the critical temperature.

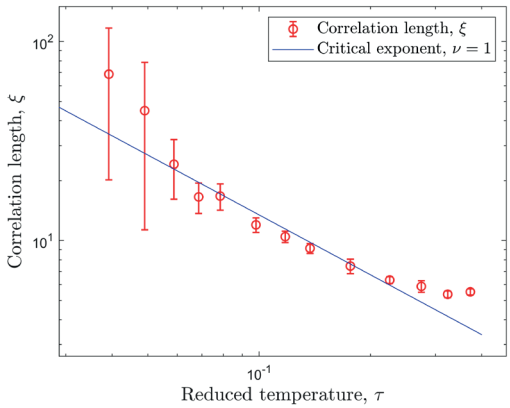

Fig. 3 The correlation length dependence on reduced temperature τ. Red symbols ◦ correspond to correlation length; vertical bars correspond to confidence interval of the averaged correlation lengths at several timesteps (confidence level 0.95). Blue solid line is the fit of the correlation length critical behavior (eq. 4)

Critical exponents phenomenologically describe the behavior of many-body systems close to criticality. The behavior of the correlation length on reduced temperature in the fluctuation region is described by the critical exponent ν:

$$\xi = \tau^{-\nu}. \tag{4}$$

Using equation (4) the critical exponent for the 2D LJ system was determined to be $\nu = 1.00 \pm 0.07$. For comparison, Table 1 shows some estimations for the critical exponent ν of two-dimensional systems. One can see agreement with the proposed method.

Table 1

Experimentally measured critical exponents of some two-dimensional systems

System	ν	Class	Ref.
Rb_2CoF_4	0.99(4)	Ising	[59], [60]
K_2CoF_4	0.97(4)	Ising	[61], [60]
Fe/W(110)	0.93(14)	Ising	[62]
LJ12–6	1.00(7)	Ising	Current work

The LJ12-6 interaction demonstrates a 2D Ising-like critical behavior [63]. For two-dimensional Ising systems it is shown that the critical exponent $\nu = 1$ [64].

Conclusion

Thus, methodology for calculating the correlator of reciprocal areas of the Voronoi cells was tested on the LJ12-6 two-dimensional system. Correlation lengths in the area above the critical transition was estimated. The critical exponent ν describing the behavior of the correlation lengths in the fluctuation region was determined. Results were compared with both experimental and theoretical data. This methodology of critical exponent estimation is well applicable for two-dimensional systems and can be applied to experimental systems of colloidal particles in the external electric rotating fields.

REFERENCES

1. **Ricard Alert, Pietro Tierno and Jaume Casademunt,** Mixed-order phase transition in a colloidal crystal, Proceedings of the National Academy of Sciences, 114.49 (2017) 12906–12909.

2. **Ahmed M. Alsayed, Mohammad F. Islam, Jian Zhang, Peter J. Collings and Arjun G. Yodh,** Premelting at defects within bulk colloidal crystals, Science, 309.5738 (2005) 1207–1210.

3. **Andrew I. Campbell, Valerie J. Anderson, Jeroen S. van Duijneveldt and Paul Bartlett,** Dynamical arrest in attractive colloids, The effect of long-range repulsion, Physical review letters, 94.20 (2005) 208301.

4. **Bing-Yang Cao, Jian-Fei Xie and Sergei S. Sazhin,** Molecular dynamics study on evaporation and condensation of n-dodecane at liquid–vapor phase equilibria, The Journal of chemical physics, 134.16 (2011) 164309.

5. **Yuan Cao, Valla Fatemi, Shiang Fang, Kenji Watanabe, Takashi Taniguchi, Efthimios Kaxiras and Pablo Jarillo-Herrero,** Unconventional superconductivity in magic-angle graphene superlattices, Nature, 556.7699 (2018) 43–50.

6. **Malcolm F. Collins,** Magnetic critical scattering. volume 4. Oxford university press, 1989.

7. **Jure Dobnikar, Alexey Snezhko and Anand Yethiraj,** Emergent colloidal dynamics in electromagnetic fields, Soft Matter, 9.14 (2013) 3693–3704.

8. **H.J. Elmers, J. Hauschild, H. Hцche, U. Gradmann, H. Bethge, D. Heuer and U. Kцhler,** Submonolayer magnetism of Fe (110) on W (110), Finite width scaling of stripes and percolation between islands, Physical review letters, 73.6 (1994) 898.

9. **Nils Elsner, C. Patrick Royall, Brian Vincent and David R.E. Snoswell,** Simple models for two-dimensional tunable colloidal crystals in rotating ac electric fields The Journal of chemical physics, 130.15 (2009) 154901.

10. **W Neil Everett, Hung-Jen Wu, Samartha G. Anekal, Hung-Jue Sue and Michael A. Bevan,** Diffusing colloidal probes of protein and synthetic macromolecule interactions Biophysical journal, 92.3 (2007) 1005–1013.

11. **Alberto Fernandez-Nieves and Antonio Manuel Puertas,** Fluids, colloids and soft materials, an introduction to soft matter physics. John Wiley & Sons, 2016.

12. **Seth Fraden, Alan J. Hurd and Robert B. Meyer,** Electric-field-induced association of colloidal particles, Physical review letters, 63.21 (1989) 2373.

13. **Hironobu Ikeda and Kinshiro Hirakawa,** Neutron scattering study of two-dimensional Ising nature of K_2CoF_4, Solid State Communications, 14.7 (1974) 529–532.

14. **Hironobu Ikeda, Masatsugu Suzuki and Michael T. Hutchings,** Neutron Scattering Investigation of Static Critical Phenomena in the Two-Dimensional Antiferromagnets: Rb_2Co c Mg1-c F_4, Journal of the Physical Society of Japan, 46.4 (1979) 1153–1160.

15. **Alexei Ivlev, Gregor Morfill, Hartmut Lowen and C Patrick Royall,** Complex plasmas and colloidal dispersions: particle-resolved studies of classical liquids and solids. volume 5. World Scientific Publishing Company, 2012.

16. **Jaime J. Júarez, Sarah E. Feicht and Michael A. Bevan,** Electric field mediated assembly of three dimensional equilibrium colloidal crystals, Soft Matter, 8.1 (2012) 94–103.

17. **L.P. Kadanoff,** Physics 2 (1966) 263; ME Fisher, Rep. Prog. Phys., 30 (1967) 615.

18. **Charles L. Kane and Eugene J. Mele,** Quantum spin Hall effect in graphene inPhysical review letters, 95.22 (2005) 226801.

19. **Kirill A. Komarov, Nikita P. Kryuchkov and Stanislav O. Yurchenko,** Tunable interactions between particles in conically rotating electric fields, Soft Matter., 14.47 (2018) 9657–9674.

20. **Markus Konig, Steffen Wiedmann, Christoph Brune, Andreas Roth, Hartmut Buhmann, Laurens W Molenkamp, Xiao-Liang Qi and Shou-Cheng Zhang,** Quantum spin Hall insulator state in HgTe quantum wells, Science, 318.5851 (2007) 766–770.

21. **Nikita P. Kryuchkov, Nikita A. Dmitryuk, Wei Li, Pavel V. Ovcharov, Yilong Han, Andrei V. Sapelkin and Stanislav O. Yurchenko,** Mean-field model of melting in superheated crystals based on a single experimentally measurable order parameter, Scientific reports, 11.1 (2021) 1–15.

22. **Nikita P. Kryuchkov, Sergey A. Khrapak and Stanislav O. Yurchenko,** Thermodynamics of two-dimensional Yukawa systems across coupling regimes, The Journal of Chemical Physics, 146.13 (2017) 134702.

23. **Nikita P. Kryuchkov, Frank Smallenburg, Alexei V. Ivlev, Stanislav O. Yurchenko and Hartmut Löwen,** Phase diagram of two-dimensional colloids with Yukawa repulsion and dipolar attraction, The Journal of chemical physics, 150.10 (2019) 104903.

24. **Volodymyr L. Kulinskii and A. Maslechko,** Surface Tension of the Liquid–Vapor Interface of the Lennard-Jones Fluids from the Ising Model, The Journal of Physical Chemistry C, 120.16 (2016) 8790–8803.

25. **Lev Davidovich Landau and Evgenii M. Lifshitz,** Statistical Physics, Volume 5. volume 5. Elsevier, 2013.

26. **Pierre-François Lenne and Vikas Trivedi,** Sculpting tissues by phase transitions, Nature Communications, 13.1 (2022) 1–14.

27. **Bo Li, Xiuming Xiao, Shuxia Wang, Weijia Wen and Ziren Wang,** Real-space mapping of the two-dimensional phase diagrams in attractive colloidal systems, Physical Review X, 9.3 (2019) 031032.

28. **Bo Li, Di Zhou and Yilong Han,** Assembly and phase transitions of colloidal crystals, Nature Reviews Materials, 1.2 (2016) 1–13.

29. **Hartmut Löwen,** Melting, freezing and colloidal suspensions, Physics Reports, 237.5 (1994) 249–324.

30. **Erik Luijten and Henk W.J. Blöte,** Boundary between long-range and short-range critical behavior in systems with algebraic interactions, Physical review letters, 89.2 (2002) 025703.

31. **F Martınez-Pedrero, J. Benet, J.E.F. Rubio, E. Sanz, R.G. Rubio and F. Ortega,** Field- induced sublimation in perfect two-dimensional colloidal crystals, Physical Review E, 89.1 (2014) 012306.

32. **Michael R. Mruzik, Farid F. Abraham and G.M. Pound,** Phase separation in fluid systems by spinodal decomposition. II. A molecular dynamics computer simulation, The Journal of Chemical Physics, 69.8 (1978) 3462–3467.

33. **Kostya S. Novoselov, D. Jiang, F. Schedin, T.J. Booth, V.V. Khotkevich, S.V. Morozov and Andre K. Geim,** Two-dimensional atomic crystals, Proceedings of the National Academy of Sciences, 102.30 (2005) 10451–10453.

34. **Pavel V. Ovcharov, Nikita P. Kryuchkov, Kirill I. Zaytsev and Stanislav O. Yurchenko,** Particle-resolved phase identification in two-dimensional condensable systems, The Journal of Physical Chemistry C, 121.48 (2017) 26860–26868.

35. **Divya Paloli, Priti S. Mohanty, Jerome J. Crassous, Emanuela Zaccarelli and Peter Schurtenberger,** Fluid–solid transitions in soft-repulsive colloids, Soft Matter., 9.11 (2013) 3000–3004.

36. **C. Patrick Royall, Dirk GAL Aarts and Hajime Tanaka,** Bridging length scales in colloidal liquids and interfaces from near-critical divergence to single particles, Nature Physics, 3.9 (2007) 636–640.

37. **Yi Peng, Feng Wang, Ziren Wang, Ahmed M. Alsayed, Zexin Zhang, Arjun G. Yodh and Yilong Han,** Two-step nucleation mechanism in solid–solid phase transitions, Nature materials, 14.1 (2015) 101–108.

38. **An T. Pham, Yuan Zhuang, Paige Detwiler, Joshua E.S. Socolar,** Patrick Charbonneau and Benjamin B Yellen. Phase diagram and aggregation dynamics of a monolayer of paramagnetic colloids, Physical Review E, 95.5 (2017) 052607.

39. **Peter N. Pusey,** Complex Plasmas and Colloidal Dispersions: Particle-Resolved Studies of Classical Liquids and Solids, Physics Today, 66.2 (2013) 48.

40. **Xiaofeng Qian, Junwei Liu, Liang Fu and Ju Li,** Quantum spin Hall effect in two-dimensional transition metal dichalcogenides, Science, 346.6215 (2014) 1344–1347.

41. **C. Patrick Royall, Mirjam E. Leunissen, Antti-Pekka Hynninen, Marjolein Dijkstra and Alfons van Blaaderen.** Re-entrant melting and freezing in a model system of charged colloids, The Journal of chemical physics, 124.24 (2006) 244706.

42. **C. Patrick Royall and Stephen R. Williams,** The role of local structure in dynamical arrest, Physics Reports, 560 (2015) 1–75.

43. **Valentin N. Ryzhov, E.E. Tareyeva, Yu.D. Fomin and Elena N. Tsiok,** Berezinskii–Kosterlitz–Thouless transition and two-dimensional melting, Physics-Uspekhi , 60.9 (2017) 857.

44. **Valentin N. Ryzhov, E.E. Tareyeva, Yu.D. Fomin and Elena N. Tsiok,** Complex phase diagrams of systems with isotropic potentials, results of computer simulations, Physics-Uspekhi, 63.5 (2020) 417.

45. **Yu Saito, Tsutomu Nojima and Yoshihiro Iwasa,** Highly crystalline 2D superconductors, Nature Reviews Materials, 2.1 (2016) 1–18.

46. **D.R.E. Snoswell, C.L. Bower, P. Ivanov, M.J. Cryan, J.G. Rarity and B. Vincent,** Dynamic control of lattice spacing within colloidal crystals, New Journal of Physics, 8.11 (2006) 267.

47. **Joris Sprakel, Alessio Zaccone, Frans Spaepen, Peter Schall and David A Weitz,** Direct observation of entropic stabilization of bcc crystals near melting, Physical Review Letters, 118.8 (2017) 088003.

48. **Anna Stradner and Peter Schurtenberger,** Potential and limits of a colloid approach to protein solutions, Soft Matter., 16.2 (2020) 307–323.

49. **Jade Taffs, Stephen R. Williams, Hajime Tanaka and C. Patrick Royall,** Structure and kinetics in the freezing of nearly hard spheres, Soft Matter., 9.1 (2013) 297–305.

50. **Shujie Tang, Chaofan Zhang, Dillon Wong, Zahra Pedramrazi, Hsin-Zon Tsai, Chunjing Jia, Brian Moritz, Martin Claassen, Hyejin Ryu, Salman Kahn and others,** Quantum spin Hall state in monolayer 1T'-WTe2, Nature Physics, 13.7 (2017) 683–687.

51. **Elena N. Tsiok, Yuri D. Fomin, Eugene A. Gaiduk, Elena E. Tareyeva, Valentin N. Ryzhov, Pavel A. Libet, Nikita A. Dmitryuk, Nikita P. Kryuchkov and Stanislav O. Yurchenko,** The role of attraction in the phase diagrams and melting scenarios of generalized 2D Lennard-Jones systems, The Journal of Chemical Physics, 156.11 (2022) 114703.

52. **Ziren Wang, Feng Wang, Yi Peng, Zhongyu Zheng and Yilong Han,** Imaging the homogeneous nucleation during the melting of superheated colloidal crystals, Science, 338.6103 (2012) 87–90.

53. **Eric R. Weeks, John C. Crocker, Andrew C. Levitt, Andrew Schofield and David A. Weitz,** Three-dimensional direct imaging of structural relaxation near the colloidal glass transition, Science, 287.5453 (2000) 627–631.

54. **Sanfeng Wu, Valla Fatemi, Quinn D. Gibson, Kenji Watanabe, Takashi Taniguchi, Robert J. Cava and Pablo Jarillo-Herrero,** Observation of the quantum spin Hall effect up to 100 kelvin in a monolayer crystal, Science, 359.6371 (2018) 76–79.

55. **Xiaoxiang Xi, Zefang Wang, Weiwei Zhao, Ju-Hyun Park, Kam Tuen Law, Helmuth Berger, Laszlo Forro, Jie Shan and Kin Fai Mak,** Ising pairing in superconducting $NbSe_2$ atomic layers, Nature Physics, 12.2 (2016) 139–143.

56. **Egor V. Yakovlev, Kirill A. Komarov, Kirill I. Zaytsev, Nikita P. Kryuchkov, Kirill I. Koshelev, Arsen K. Zotov, Dmitry A. Shelestov, Victor L. Tolstoguzov, Vladimir N. Kurlov, Alexei V. Ivlev and others,** Tunable two-dimensional assembly of colloidal particles in rotating electric fields, Scientific reports, 7.1 (2017) 1–10.

57. **Egor V. Yakovlev, Nikita P. Kryuchkov, Sofia A. Korsakova, Nikita A. Dmitryuk, Pavel V. Ovcharov, Mihail M. Andronic, Ilya A. Rodionov, Andrei V. Sapelkin and Stanislav O. Yurchenko,** 2D

colloids in rotating electric fields: A laboratory of strong tunable three- body interactions, Journal of Colloid and Interface Science, 608 (2022) 564–574.

58. **Heejun Yang, Sung Wng Kim, Manish Chhowalla and Young Hee Lee,** Structural and quantum-state phase transitions in van der Waals layered materials, Nature Physics, 13.10 (2017) 931–937.

59. **Anand Yethiraj and Alfons van Blaaderen,** A colloidal model system with an interaction tunable from hard sphere to soft and dipolar, nature, 421.6922 (2003) 513–517.

60. **Alessio Zaccone, Jerome J. Crassous and Matthias Ballauff,** Colloidal gelation with variable attraction energy, The Journal of chemical physics, 138.10 (2013) 104908.

61. **Klaus Zahn, R. Lenke and Georg Maret,** Two-stage melting of paramagnetic colloidal crystals in two dimensions, Physical review letters, 82.13 (1999) 2721.

62. **Klaus Zahn and Georg Maret,** Dynamic criteria for melting in two dimensions, Physical Review Letters, 85.17 (2000) 3656.

63. **Isla Zhang, C. Patrick Royall, Malcolm A. Faers and Paul Bartlett,** Phase separation dynamics in colloid–polymer mixtures, the effect of interaction range, Soft Matter , 9.6 (2013) 2076–2084.

64. **Chao Zhu, Suxia Liang, Erhong Song, Yuanjun Zhou, Wen Wang, Feng Shan, Yantao Shi, Ce Hao, Kuibo Yin, Tong Zhang and others,** In-situ liquid cell transmission electron microscopy investigation on oriented attachment of gold nanoparticles, inNature communications, 9.1 (2018) 1–7.

THE AUTHORS

SIMKIN Ivan V.
vanyasimkin@gmail.com
ORCID: 0000-0003-1650-4177

YAKOVLEV Egor V.
yakov.egor@gmail.com
ORCID: 0000-0001-5093-2349

KRYUCHKOV Nikita P.
kruchkov_nkt@mail.ru
ORCID: 0000-0002-9085-1284

KORSAKOVA Sofia A.
sofia.korsakova@gmail.com

YURCHENKO Stanislav O.
st.yurchenko@mail.ru
ORCID: 0000-0001-6821-904X

Received 23.11.2022. Approved after reviewing 06.12.2022. Accepted 12.12.2022.