CHIN. PHYS. LETT. Vol. 34, No. 9 (2017) 092101

Collective Flows of $^{16}O+^{16}O$ Collisions with α-Clustering Configurations *

Chen-Chen Guo(郭琛琛)[1], Wan-Bing He(何万兵)[2], Yu-Gang Ma(马余刚)[1,3,4**]

[1]*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800*
[2]*Institute of Modern Physics, Fudan University, Shanghai 200433*
[3]*University of Chinese Academy of Sciences, Beijing 100049*
[4]*School of Physical Science and Technology, ShanghaiTech University, Shanghai 200031*

(Received 9 June 2017)

The main purpose of the present work is to discuss whether or not the collective flows in heavy-ion collision at the Fermi energy can be taken as a tool to investigate the cluster configuration in light nuclei. In practice, within an extended quantum molecular dynamics model, four α-clustering (linear chain, kite, square and tetrahedron) configurations of ^{16}O are employed in the initialization, $^{16}O+^{16}O$ around the Fermi energy (40–60 MeV/nucleon) with impact parameter 1–3 fm are simulated, and the directed and elliptic flows are analyzed. It is found that collective flows are influenced by the different α-clustering configurations, and the directed flow of free protons is more sensitive to the initial cluster configuration than the elliptic flow. Nuclear reaction at the Fermi energy can be taken as a useful way to study cluster configuration in light nuclei.

PACS: 21.65.Cd, 21.65.Mn, 25.70.−z DOI: 10.1088/0256-307X/34/9/092101

With the rapid development in both theoretical and experimental methods, α clustering structure in light nuclei has attracted much attention in recent decades.[1−3] There are various theoretical models to study the α cluster in light nuclei, e.g., the *ab initio* method,[4,5] the fermion molecular dynamics model (FMD),[6,7] the antisymmetric molecular dynamics model (AMD),[8−11] the extended quantum molecular dynamics model (EQMD),[12−16] the α-cluster model,[17] the algebraic cluster model, and [18] the covariant density functional theory.[19] Regarding the α-clustering configuration in ^{16}O, the chain configuration of 4α clusters in ^{16}O was investigated using a Skyrme cranked Hartree–Fock method[20] as well as the Brink wave functions,[21] while a tetrahedral configuration of α clusters was discussed in Refs. [22,23]. In the experimental point of view, however, the whole picture of α-clustering configuration in nucleus has still not emerged so far although some experimental signs have been indicated for information of α clusters in nuclei.[2,22,24] It is necessary to find more observables to explore cluster configuration in nuclei.

Recently, it was proposed to use collective flows in relativistic nuclear collisions to probe α-clustering in light nuclei, which offers a new idea for investigating the cluster configuration.[25−27] Collective flow, which has been studied over a wide range of beam energies and reaction systems, is one of the most important observables to probe the nuclear equation of state, the in-medium nucleon–nucleon cross section, the quark–gluon plasma, the viscosity and so on.[28−41] Thus it is very interesting to evaluate whether it can be used to probe the cluster configuration in light nuclei at the Fermi energies.

In this work, within an extended quantum molecular dynamics (EQMD) model, the influence of cluster configuration on collective flows of protons produced in $^{16}O+^{16}O$ collisions at the Fermi energy is investigated. The EQMD model is based on the quantum molecular dynamics (QMD) model, which is an N-body approach considering several improvements, and the approaches can be used to simulate nuclear reaction and meson-induced reaction at both very low energies and relativistic energies.[42] In the QMD-type model, each nucleon is represented by a Gaussian wave packet. In the initialization of projectile and target in QMD-type models, the centers of the Gaussian wave packet of nucleons are randomly chosen in coordinate space between 0 and the radius of projectile or target as well as momentum space between 0 and the Fermi momentum at the local density with consideration of several constraints, such as a proper binding energy, density and momentum distributions. However, the initialized nuclei are not always at their ground state (energy-minimum state), thus some unexpected nucleons are emitted during the collision process even at zero temperature. To solve those problems, an extended version of the QMD model was developed by Maruyama *et al.*, named as EQMD.[43] In the EQMD model, unlike the standard QMD model, the width of Gaussian wave packet of nucleon is a complex and has the form, i.e., $\nu_i \equiv \frac{1}{\lambda_i} + i\delta_i$, where λ_i and δ_i are its real and imaginary parts which are also time-dependent, respectively. The Gaussian wave packet is

$$\phi_i(\boldsymbol{r};t) = \left(\frac{\nu_i + \nu_i^*}{2\pi}\right)^{3/4} \exp\Big[-\frac{\nu_i}{2}(\boldsymbol{r} - \boldsymbol{r}_i(t))^2 + \frac{i}{\hbar}\boldsymbol{r}\cdot\boldsymbol{p}_i(t)\Big], \quad (1)$$

where $\boldsymbol{r}_i(t)$ and $\boldsymbol{p}_i(t)$ are the centers of wave packet of nucleon i in the coordinate and momentum space, respectively. The total wave function of an N-body sys-

*Supported by the National Natural Science Foundation of China under Grant Nos 11421505, 11220101005, 11305239 and 11605270, the Major State Basic Research Development Program of China under Grant No 2014CB845401, the Key Research Program of Frontier Sciences of the Chinese Academy of Sciences under Grant No QYZDJ-SSW-SLH002, and the China Postdoctoral Science Foundation under Grant No 2016M591730.

**Corresponding author. Email: ygma@sinap.ac.cn

© 2017 Chinese Physical Society and IOP Publishing Ltd

tem is assumed as the direct product of the Gaussian wave packet, i.e., $\Psi = \prod_i \phi_i(\boldsymbol{r};t)$. The Hamiltonian of the system is given as

$$H = \left\langle \Psi \middle| \sum_i -\frac{\hbar^2}{2m}\nabla_i^2 - \hat{T}_{\rm c.m.} + \hat{H}_{\rm int} \middle| \Psi \right\rangle = \sum_i \left[\frac{\boldsymbol{p}_i(t)^2}{2m} + \frac{3\hbar^2(1+\lambda_i^2\delta_i^2)}{4m\lambda_i}\right] - T_{\rm c.m.} + H_{\rm int}, \quad (2)$$

where $T_{\rm c.m.}$ denotes the spurious zero-point center-of mass kinetic energy caused by the zero-point oscillation of the center-of-mass wave function of the clusters. The subtraction of the spurious zero-point center-of mass kinetic energy is necessary for reproducing binding energy of nuclei and cannot be ignored when one studies nuclear structure and reaction at low energies; more details about $T_{\rm c.m.}$ can be found in Ref. [44]. Here $H_{\rm int}$ is the potential energy term, which contains several parts as follows:

$$H_{\rm int} = H_{\rm Skyrme} + H_{\rm Coulomb} + H_{\rm Symmetry} + H_{\rm Pauli}, \quad (3)$$

where $H_{\rm Skyrme}$, $H_{\rm Coulomb}$, $H_{\rm Symmetry}$ and $H_{\rm Pauli}$ are the Skyrme, Coulomb, symmetry and Pauli potential terms, respectively. More details can be found in Ref. [43]. Recently, the EQMD model was also extended to treat photonuclear reactions.[14,45,46]

In our previous studies, different α-clustering structures and their effects on dipole resonance and photonuclear reactions of ^{16}O and ^{12}C have been investigated.[12–14] Here, to study the influence of initial α-cluster configurations on the collective flow, four configurations, namely linear chain, kite, square and tetrahedron of 4-α structure for ^{16}O are employed at the initialization, and random orientations are used to obtain the initial state for ^{16}O+^{16}O. More than 600000 events for each configuration are simulated, to reduce statistical error for observables.

Figure 1 shows the directed flow parameter $v_1 = \langle \frac{p_x}{p_t} \rangle$ and the elliptic flow parameter $v_2 = \langle \frac{p_x^2 - p_y^2}{p_t^2} \rangle$ of free protons as a function of the longitudinal rapidity $y_z = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$, where $p_t = \sqrt{p_x^2 + p_y^2}$ is the transverse momentum of emitted particles, p_z is the z-component of momentum, and E is the total energy in the center-of-mass system. As usual, the x-axis is defined to be along the impact parameter vector, the z-axis is along the beam direction, and the y-axis is perpendicular to the reaction plane (xz-plane). First, in Fig. 1(a) we clearly see that the directed flow parameter v_1 decreases with increasing rapidity, called negative flow, which means that particles are more likely to undergo a rotational-like motion rather than a bounce-off motion. The value of the elliptic flow parameter v_2 at mid-rapidity ($y_z = 0$) are sightly larger than zero, as seen in Fig. 1(b), which implies a preferential in-plane emission rather than an out-of-plane emission pattern. Indeed, the observed negative directed flow and in-plane elliptic flow around the Fermi energy have been well established in both experimental and theoretical studies.[28,32,47,48] This results from the domination of the attractive part of the nucleon–nucleon interaction over the repulsive part on the nucleon–nucleon scattering. Secondly, v_1 of protons produced from the tetrahedron (more compact shape) configuration is much negative than that from the chain (less compact shape) configuration, because of a stronger interaction originating from a higher density in collisions with the former configuration (as will be seen in Fig. 2). In addition, we can see that the differences in v_1 and v_2 between different cluster configurations become noticeable around the projectile/target rapidity region. From Fig. 1(b), we find that the calculated v_2 at mid-rapidity from the tetrahedron configuration is sightly smaller than that from the chain configuration, while the situation is reverse around the target and projectile rapidities. This phenomenon may result from two factors: (i) relatively more violent two-body scatterings in the tetrahedron configuration determined by the initial geometry lead to smaller values of v_2 (towards out-of-plane emission) at mid-rapidity; (ii) weaker interactions existing in the quasi-projectile and quasi-target region in the chain configuration weaken the rotational-like motion of nucleons. In general, we note that the directed flow of free protons is more sensitive to the initial cluster configuration than the elliptic flow.

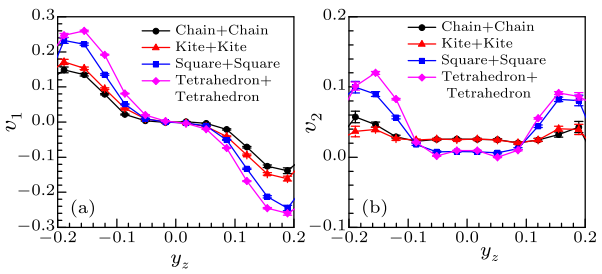

Fig. 1. The directed flow parameter v_1 (a) and elliptic flow parameter v_2 (b) for free protons as a function of the longitudinal rapidity y_z for ^{16}O+^{16}O collisions at 40 MeV/nucleon and $b = 3$ fm.

To better understand the influence of initial configuration on the reaction dynamic process, time evolution of the nucleon density in the reaction plane for ^{16}O+^{16}O collisions at 40 MeV/nucleon is shown in Fig. 2 as an example. At initial stage (here $t = 100$ fm/c, because the projectile and target nuclei are put far away), see Figs. 2(a), 2(d), 2(g) and 2(j), the nucleon density contours for those four different configurations have almost spherical shapes. This is because the initial configurations are randomly orientated for all the events, and 1000 events are accumulated to draw these contour plots. Nevertheless, the differences among them can be seen. It is understandable that the contour of nucleon density for the chain configuration is the largest, while for the tetrahedron configuration it is the smallest. The difference in the density distribution at the initial stage will certainly affect the density evolution afterwards. As can be seen in the last two columns of Fig. 2, at $t = 160$ fm/c, the nucleon density in the center of the

compressed region slightly increases from the chain to the tetrahedron configuration, and at $t = 200$ fm/c, the nucleon density in the center of the quasi-projectile and quasi-target region also increases from the chain to the tetrahedron configuration. Different densities achieved during the reaction would lead to different pressures, therefore one can see that the final observables such as collective flows are influenced by the initial configuration.

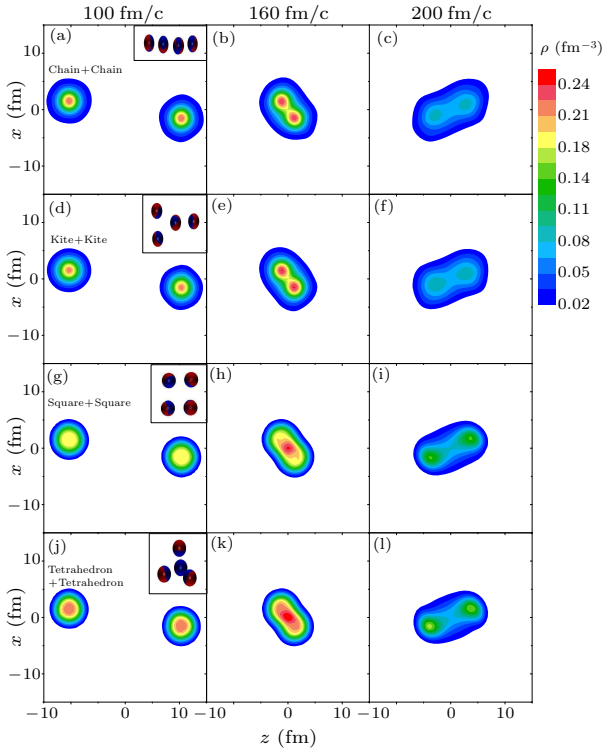

Fig. 2. Contour plots of the average nucleon density in the reaction plane of ^{16}O+^{16}O collisions at 40 MeV/nucleon. Simulations with the chain [panels (a), (b), and (c)], kite [panels (d), (e), and (f)], square [panels (g), (h), and (i)], and tetrahedron [panels (j), (k), and (l)] configurations at three different times (100 fm/c, 160 fm/c, and 200 fm/c) are shown. In the insets of (a), (d), (g) and (j), sketches for the four different α-clustering configurations are plotted. Here 1000 events were collected to make the statistical error small enough.

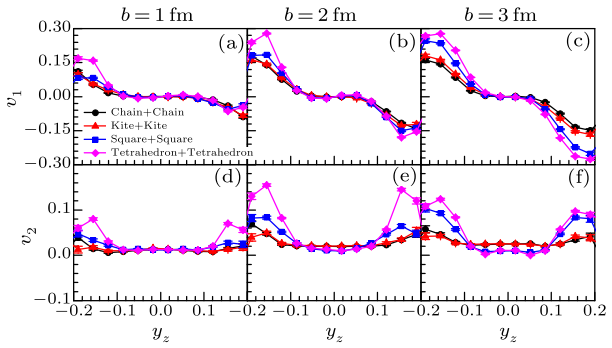

Fig. 3. The directed flow parameter v_1 (upper panels) and elliptic flow parameter v_2 (lower panels) of free protons in ^{16}O+^{16}O collisions at 40 MeV/nucleon with impact parameters of 1, 2 and 3 fm, as a function of the longitudinal rapidity y_z.

To exhibit more systematically the influence of cluster configuration on the collective flows, ^{16}O+^{16}O reaction with different impact parameters and beam energies are focused on. The results of the directed and elliptic flows of free protons are shown in Figs. 3 and 4. As we can see from upper panels of Fig. 3, the difference between different cluster configurations is more evident for the larger impact parameters. We have checked that the difference in the nucleon density contour in the reaction plane increases with the impact parameter, which results in a larger sensitivity of the directed flow to the cluster configuration. For more central collision, the collision number is hardly influenced by cluster configuration due to random orientations of the initial projectile and target, while for more peripheral collision, the collision number is strongly dependent on the initial geometry, thus the flow is sensitive to the cluster configuration. The directed flow at different beam energies is shown in Fig. 4. The sensitivity of the directed flow to the cluster configuration decreases with increasing the beam energy, e.g., at 60 MeV/nucleon, we can see almost the same directed flow with different cluster configurations. In Figs. 3 and 4, we find that the elliptic flow is less sensitive to different cluster configurations than the directed flow. Beam energy below 40 MeV/nucleon is not considered, because nuclei are more likely to undergo fusion then the collective flows of nucleons become quite weak. The energy dependence of collective flow in HICs has been widely studied both experimentally and theoretically (see, e.g., Refs. [47,48]). With increasing the beam energy, the multiple scattering process is dominant in comparison with the contribution coming from the effect of the clustering configuration.

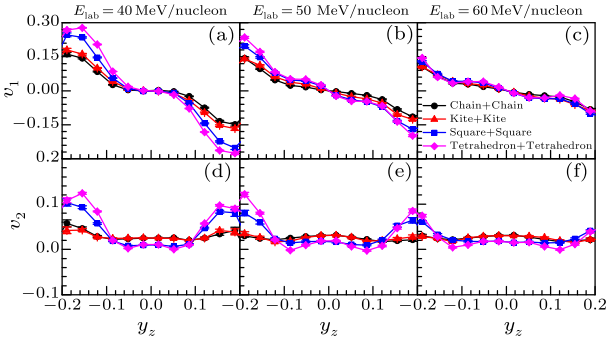

Fig. 4. The same as Fig. 3, but for ^{16}O+^{16}O collisions at beam energies of 40, 50 and 60 MeV/nucleon with impact parameter of $b = 3$ fm.

In summary, ^{16}O+^{16}O reactions with the linear chain, kite, square, and tetrahedron 4-α configurations around the Fermi energy have been simulated by the EQMD model and their directed and elliptic flows of free protons are focused on. It is found that the directed flow of protons produced from the tetrahedron configuration is more negative than that from the chain configuration, while in-plane elliptic flow from the tetrahedron configuration is smaller than that from the chain configuration. This can be understood from the difference in the mean-field potential and two-body scattering caused by the initial geome-

try. Moreover, we also found that the directed flow of protons shows a larger sensitivity to the initial cluster configuration than the elliptic flow. In addition, through the simulation of ^{16}O+^{16}O reaction at different impact parameters and beam energies, it is shown that the directed flow from reaction with a larger impact parameter and a smaller beam energy (around 40 MeV/nucleon) is suggested for future measurement to probe the cluster configuration in ^{16}O. From an experimental point of view, a precise measurement of the collective flow is relatively easier for a larger colliding system due to the better determination of the reaction plane. Thus it would probably be advisable to investigate the cluster configuration with nuclear reaction, such as ^{16}O(^{12}C)+^{124}Sn (^{197}Au). In a future study, such reactions will be simulated within the same microscopic transport model. Finally, it should be mentioned that here we did not touch the study of high-order flows, such as triangular flow (v_3) and 4th flow (v_4), which have been extensively studied in relativistic heavy ion collision.[26,35] In principle, v_3 and v_4 will be significant for nuclear reaction with triangle 3-α clustering nuclei (^{12}C) and 4-α clustering nucleus (^{16}O), respectively. Anyway, such high-order flows leave us a topic to be addressed in the near future.

We thank Professor Qingfeng Li for helpful discussions and acknowledge support by the computing server C3S2 in Huzhou University.

References

[1] Oertzen W, Freer M and Kanada-Eno Y 2006 *Phys. Rep.* **432** 43
[2] Freer M 2007 *Rep. Prog. Phys.* **70** 2149
[3] Cao X G and Ma Y G 2015 *Chin. Sci. Bull.* **60** 1557
[4] Epelbaum E, Krebs H, Lee D and Meissner U G 2011 *Phys. Rev. Lett.* **106** 192501
[5] Epelbaum E, Krebs H, Lahde T A, Lee D and Meissner U G 2012 *Phys. Rev. Lett.* **109** 252501
[6] Feldmeier H 1990 *Nucl. Phys.* A **515** 147
[7] Chernykh M, Feldmeier H, Neff T, Neumann-Cosel P and Richter A 2007 *Phys. Rev. Lett.* **98** 032501
[8] Kanada-En'yo Y, Kimura M and Ono A 2012 *Prog. Theor. Exp. Phys.* **2012** 01A202
[9] Kanada-En'yo Y et al 2015 *Nucl. Sci. Tech.* **26** S20501
[10] Ma C W et al 2016 *Nucl. Sci. Tech.* **27** 111
[11] Ma C W et al 2015 *Chin. Phys. Lett.* **32** 072501
[12] He W B, Ma Y G, Cao X G, Cai X Z and Zhang G Q 2014 *Phys. Rev. Lett.* **113** 032506
[13] He W B, Ma Y G and Zhang Q G 2016 *Phys. Rev.* C **94** 014301
[14] Huang B S, Ma Y G and He W B 2017 *Phys. Rev.* C **95** 034606
Huang B S, Ma Y G and He W B 2017 *Eur. Phys. J.* A **53** 119
[15] He W B, Ma Y G, Cao X G et al 2014 *Nucl. Tech.* **37** 100511 (in Chinese)
[16] Wang S S, Cao X G, Zhang T L et al 2015 *Nucl. Phys. Rev.* **32** 24
[17] Halcrow C J, King C and Manton N S 2017 *Phys. Rev.* C **95** 031303
[18] Bijker R 2010 *AIP Conf. Proc.* **1323** 28
[19] Zhou E F, Yao J M, Li Z P, Meng J and Ring P 2016 *Phys. Lett.* B **753** 227
[20] Ichikawa T, Maruhn J A, Itagaki N and Ohkubo S 2011 *Phys. Rev. Lett.* **107** 112501
[21] Suhara T, Funaki Y, Zhou B, Horiuchi H and Tohsaki A 2014 *Phys. Rev. Lett.* **112** 062501
[22] Bijker R and Iachello F 2014 *Phys. Rev. Lett.* **112** 152501
[23] Epelbaum E et al 2014 *Phys. Rev. Lett.* **112** 102501
[24] Tian Z Y, Ye Y L, Li Z H et al 2016 *Chin. Phys.* C **40** 111001
[25] Broniowski W and Arriola W R 2014 *Phys. Rev. Lett.* **112** 112501
[26] Zhang S, Ma Y G, Chen J H et al 2017 *Phys. Rev.* C **95** 064904
[27] Bozek P, Broniowski W, Ruiz A E and Rybczynski M 2014 *Phys. Rev.* C **90** 064902
[28] Reisdorf W and Ritter H G 1997 *Annu. Rev. Nucl. Part. Sci.* **47** 663
[29] Stoecker H 2005 *Nucl. Phys.* A **750** 121
[30] Kumar S and Ma Y G 2013 *Nucl. Sci. Tech.* **24** 050509
[31] Ko C M, Chen L W, Vincenzo G et al 2013 *Nucl. Sci. Tech.* **24** 050525
[32] Ma Y G et al 1993 *Phys. Rev.* C **48** R1492
Ma Y G et al 1995 *Phys. Rev.* C **51** 1029
[33] Yan T Z, Ma Y G, Cai X Z et al 2006 *Phys. Lett.* B **638** 50
[34] Chen J H, Ma Y G, Ma G L et al 2006 *Phys. Rev.* C **74** 064902
[35] Han L X, Ma G L, Ma Y G et al 2011 *Phys. Rev.* C **84** 064907
[36] Xie W J and Feng Z Q 2015 *Chin. Phys. Lett.* **32** 122502
[37] Zhang F 2016 *Chin. Phys. Lett.* **33** 012501
[38] Zhou C L, Ma Y G, Fang D Q et al 2014 *Phys. Rev.* C **90** 057601
[39] Song H C, Zhou Y and Gajdoov K 2017 *Nucl. Sci. Tech.* **28** 99
[40] Xu Z Y et al 2017 *Chin. Phys. Lett.* **34** 062501
[41] Wang T T et al 2015 *Chin. Phys. Lett.* **32** 062501
[42] Aichelin J 1991 *Phys. Rep.* **202** 233
[43] Maruyama T, Niita K and Iwamoto A 1996 *Phys. Rev.* C **53** 297
[44] Ono A and Horiuchi H 2004 *Prog. Part. Nucl. Phys.* **53** 501
[45] Huang B S and Ma Y G 2017 *Chin. Phys. Lett.* **34** 072401
[46] Wu H L et al 2015 *Nucl. Sci. Tech.* **26** 050103
[47] Andronic A, Lukasik J, Reisdorf W et al 2006 *Eur. Phys. J.* A **30** 31
[48] Li Q F, Shen C W, Guo C C et al 2011 *Phys. Rev.* C **83** 044617