

**Translocation of Heterogeneous Flexible Polymers Assisted by Binding Particles**

Yu Wan-Cheng

Cite this article as:

Yu Wan-Cheng. Translocation of Heterogeneous Flexible Polymers Assisted by Binding Particles[J]. *Chinese J. Polym. Sci.*, 2020, 38(7): 784-790. doi: 10.1007/s10118-020-2387-9

View online: <https://doi.org/10.1007/s10118-020-2387-9>

---

**Articles you may be interested in**

**TRANSLOCATION OF A PROTEIN-LIKE CHAIN THROUGH AN INTERACTING CHANNEL**

Chinese J. Polym. Sci. 2011, 29(5): 520 <https://doi.org/10.1007/s10118-011-1067-1>

**PRELIMINARY STUDY OF EXTRACTABLE PROTEIN BINDING USING MALEIC ANHYDRIDE COPOLYMER**

Chinese J. Polym. Sci. 2012, 30(2): 181 <https://doi.org/10.1007/s10118-012-1112-8>

**DEFORMATION OF COPOLYMER MICELLES INDUCED BY AMPHIPHILIC DIMER PARTICLES**

Chinese J. Polym. Sci. 2012, 30(2): 164 <https://doi.org/10.1007/s10118-012-1108-4>

**流场中单链高分子过孔输运的动力学行为**

Dynamics of Single Polymer Translocation Through a Fluidic Nanopore

高分子学报. 2015(10): 1196 <https://doi.org/10.11777/j.issn1000-3304.2015.15069>

**硅胶表面铜(Ⅱ)离子印迹聚乙烯亚胺的制备及结合特性研究**

STUDIES ON PREPARATION OF ION-IMPRINTED POLYETHYLENEIMINE ON SILICA GEL PARTICLES AND BINDING PROPERTIES FOR METAL IONS

高分子学报. 2007(4): 366

**流场驱动高分子链迁移穿过微通道的耗散粒子动力学模拟**

DISSIPATIVE PARTICLE DYNAMICS SIMULATIONS OF FLUID-DRIVEN POLYMER CHAINS THROUGH A MICROCHANNEL

高分子学报. 2012(2): 160 <https://doi.org/10.3724/SP.J.1105.2012.11117>

# Translocation of Heterogeneous Flexible Polymers Assisted by Binding Particles

Wan-Cheng Yu\*

Department of Physics, School of Physics, Beihang University, Beijing 100191, China

**Abstract** A polymer chain usually contains two or more types of monomeric species from the perspective of polymer chemistry, which poses a challenge to the understanding of structure-property relationships. It is of course true in the field of polymer translocation. In the present work, I investigate the translocation dynamics of heterogeneous flexible polymers composed of two types of monomers labeled A and B through a nanopore assisted by binding particles (BPs) by using the coarse-grained Langevin dynamics simulations in two-dimensional domains. Specifically, multiblock copolymers with different block lengths and monomeric components are considered. I critically examine how the translocation dynamics responds to the variations in the block length and the monomeric content. Interestingly, it is found that the periodic structure of a multiblock copolymer causes an obvious fingerprint feature in the residence time of individual monomers in which the number of peaks is exactly equal to the number of blocks. These findings provide a basic understanding about the sequence-dynamics relationship for the BPs-assisted translocation of heterogeneous flexible polymers.

**Keywords** Polymer translocation; Multiblock copolymer; Binding particles; Langevin dynamics simulations

**Citation:** Yu, W. C. Translocation of heterogeneous flexible polymers assisted by binding particles. *Chinese J. Polym. Sci.* 2020, 38, 784–790.

## INTRODUCTION

Translocation of biological polymers, such as DNA, mRNA and proteins through pores or channels at nanoscale, plays important roles in maintaining vital activities.<sup>[1]</sup> The significance of studying polymer translocation in the context of biology is not only to develop a better understanding about how life works at a molecular level, but also to inspire people to think deeply about what human can do by learning from the nature. Thanks to the seminal work of Kasianowicz *et al.*<sup>[2]</sup> in 1996, great technical advances in nanopore-based sequencing have been made nowadays. A typical example is that based on the creative work of Bayley,<sup>[3]</sup> the commercial applications of nanopore-based DNA sequencing technology are making steady progress promoted by high-tech enterprises such as Oxford Nanopore Technologies. The ultimate realization of nanopore-based DNA sequencing with high accuracy, long read length, high throughput and low cost might come true in the near future.

From the view of physics, a polymer chain inflicts a large energy penalty caused by a great loss of conformational entropy during its translocation through a nanopore. Therefore, the efficient polymer translocation requires a driving force. The origin of driving force can be from the trans-membrane electrical potential,<sup>[4–7]</sup> a pulling force,<sup>[8,9]</sup> a fluid flow,<sup>[10–13]</sup> the trans-membrane chemical potential gradient,<sup>[14–19]</sup> etc.

In this study, I focus on the translocation induced by the trans-membrane chemical potential gradient. In this case, polymer translocation could be induced by the selective adsorption of monomers in the *trans* side of the membrane,<sup>[14–16]</sup> and the different solvent qualities on two sides of the membrane.<sup>[17–19]</sup> In living cells, the inhomogeneous distribution of binding particles (BPs) such as chaperones that own the affinity to proteins to be translocated across the biological membrane can induce a trans-membrane chemical potential gradient. Biological examples of polymer translocation assisted by BPs include the translocation of proteins through mitochondrial membrane<sup>[20–22]</sup> and the passage of DNA through membranes.<sup>[23,24]</sup> In what follows, I pay attention to polymer translocation in the presence of BPs.

Up to now, the fundamental mechanism of BPs-assisted polymer translocation through a nanopore has been clarified. Namely, the binding of BPs to chain monomers provides an effective driving force that pulls the chain across the membrane.<sup>[25–42]</sup> It is worth noting that these previous works were based on the stiff chain limit. It is a reasonable method for tackling the most fundamental questions like the translocation mechanism by using the stiff chain model, as it could capture the underlying physical nature of the translocation process. However, more realistic modelings of a polymer chain are necessary to mimic real systems. For instance, the intrinsic chain flexibility has been taken into account.<sup>[43–47]</sup> It has been suggested that due to the formation of the complex of BPs-monomers, the conformation of translocated subchains has significant effects on the detailed translocation dy-

\* Corresponding author, E-mail: ywcheng@buaa.edu.cn

Received December 6, 2019; Accepted January 11, 2020; Published online February 27, 2020

namics.<sup>[43–45]</sup> More recently, Suhonen and Linna have revealed that the binding mechanism, *i.e.*, whether an BP binds to a single site or multiple sites, would give rise to substantial differences in the translocation dynamics of flexible polymers in three dimensions.<sup>[46]</sup>

For polymer translocation, the heterogeneities along the chain have always been a concern, which could arise from the variation of monomeric species<sup>[48–52]</sup> or local stiffness<sup>[53,54]</sup> along the chain. For BPs-assisted polymer translocation, the effects of heterogeneous polymer sequence on the translocation dynamics have been studied theoretically by Abdolvahab *et al.* in the limit of stiff chains.<sup>[35–37]</sup> Nevertheless, the translocation dynamics of heterogeneous flexible polymers remains unsolved to the best of my knowledge, which motivates me to conduct the present study.

What I concern in this work is how the dynamics of BPs-assisted polymer translocation through a nanopore makes a response to the variations in the chain sequence structure. For this purpose, multiblock copolymers composed of two types of monomeric species labeled A and B are studied. The only difference between the monomer A and the monomer B is their different affinities with BPs. Data gathered from the two-dimensional Langevin simulations would answer the following questions: (1) How does the magnitude of the block length affect the translocation dynamics? (2) If there is a change in the monomeric content of the multiblock copolymer, how would the translocation dynamics respond? With these issues being figured out, I hope to establish a basic understanding about the sequence-dynamics relationship for heterogeneous polymer translocation through a nanopore assisted by BPs. The remainder of this paper is organized as follows. The model and the simulation technique are briefly elaborated in the second section. I present results and corresponding discussions in the third section. Finally, a brief summary is given in the last section.

## MODEL AND METHODS

As sketched in Fig. 1, the translocation of a multiblock copolymer through a nanopore in the presence of BPs is considered. Here, the classical finitely extensible bead-spring chain model<sup>[55]</sup> is used to mimic the multiblock copolymers. Each bead of a diameter  $\sigma$  in the chain represents a monomer. By applying the finite extension nonlinear elastic (FENE) potential, adjacent beads along the chain are connected:

$$U_{\text{FENE}}(r) = -\frac{1}{2}kR_0^2 \ln\left(1 - r^2/R_0^2\right) \quad (1)$$

where  $r$  is the distance between consecutive beads,  $k$  is the spring constant, and  $R_0$  is the maximum allowed separation between connected beads.

The multiblock copolymers studied in this work are deemed to be in good solvents where the excluded volume interactions dominate. In the simulations, this can be achieved by applying a purely repulsive truncated Lennard-Jones (LJ) potential with a cutoff distance  $r_{\text{cut},1} = 2^{1/6}\sigma$  between beads:

$$U_{\text{LJ}}(r) = \begin{cases} 4\epsilon_0 \left[ \left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^6 \right] + \epsilon_0, & r \leq 2^{1/6}\sigma \\ 0, & r > 2^{1/6}\sigma \end{cases} \quad (2)$$

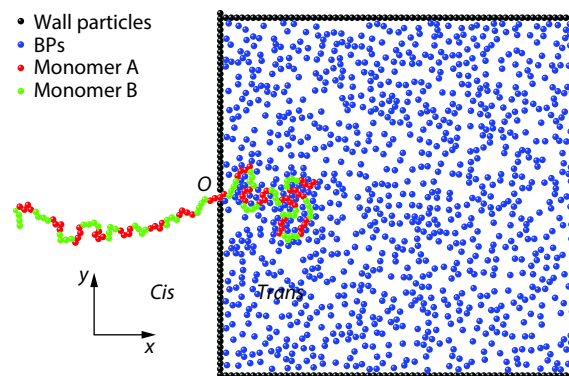


**Fig. 1** Two-dimensional schematic illustration of a multiblock copolymer with a total number of monomers  $N = 128$  translocating into a chamber wherein binding particles (solid blue circles) randomly diffuse. The multiblock copolymer is composed of two types of monomeric species labeled A (solid red circles) and B (solid green circles). Binding particles interact attractively with chain monomers with different binding strengths depending on the monomeric species,  $\epsilon_A = 4.0\epsilon_0$  and  $\epsilon_B = 2.0\epsilon_0$ . The shown multiblock copolymer has a sequence structure  $\text{Poly}(\text{A}_4\text{B}_4)_{16}$ . The chamber size is  $L_x \times L_y = 64\sigma \times 64\sigma$ . The center of the nanopore is placed at the origin of coordinate. The pore has a length  $L = \sigma$  and a width  $W = 1.6\sigma$ , respectively. See the text for the used units  $\epsilon_0$  and  $\sigma$ .

where  $\epsilon_0$  is the depth of the potential well, and  $r$  is the distance between a pair of beads.

BPs diffuse randomly in a rectangular chamber of a size  $L_x \times L_y = 64\sigma \times 64\sigma$ , and the same short-ranged repulsive LJ potential (Eq. 2) is exerted to BPs. Therefore, they repel each other and can be considered as uniform distributed before the translocation. Translocation of multiblock copolymers is assisted by the binding of BPs to the monomers that get through the nanopore. The multiblock copolymer is composed of two types of monomeric species labeled A (solid red circles) and B (solid green circles), as depicted in Fig. 1. Binding of BPs relies on their attractive interactions with the monomer A and the monomer B. It can be realized by applying a longer-ranged LJ potential with a cutoff distance  $r_{\text{cut},2} = 2.5\sigma$  between monomers and BPs:

$$U_{\text{LJ}}(r) = \begin{cases} 4\epsilon_{A,B} \left[ \left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^6 \right] + \epsilon_{A,B}, & r \leq 2.5\sigma \\ 0, & r > 2.5\sigma \end{cases} \quad (3)$$

where  $\epsilon_{A,B}$  is the binding strength. In this work, the monomer A has a stronger affinity with BPs. The choice of the binding strengths is  $\epsilon_A = 4.0\epsilon_0$  and  $\epsilon_B = 2.0\epsilon_0$ . The LJ parameters  $\epsilon_0$ ,  $\sigma$  and bead mass  $m$  determines the energy, length and mass scales of the system, respectively. Subsequently, the corresponding time scale  $t_{\text{LJ}} = (m\sigma^2/\epsilon_0)^{1/2}$  and force scale  $\epsilon_0/\sigma$  can be obtained, which are order of ps and pN, respectively. The parameters for all simulations in this work are chosen to be  $R_0 = 1.5\sigma$ ,  $k = 30\epsilon_0/\sigma^2$ ,  $\xi = 0.7/t_{\text{LJ}}$  and temperature  $k_B T = 1.2\epsilon_0$ .

The walls forming the closed chamber consist of static particles separated from each other by a distance  $\sigma$ . The nanopore of a length  $L = \sigma$  and a width  $W = 1.6\sigma$  is embedded in the leftmost wall, and its center is placed at the origin of coordinate  $O(0,0)$ . In this work, the number of BPs inside the chamber is fixed at  $N_{\text{BPs}} = 1040$ , and thus a constant area fraction at  $\phi_{\text{BPs}} = 25.39\%$ . The choice of  $\phi_{\text{BPs}} = 25.39\%$  in this work is to ensure that the present setup could detect the vari-

ations in the monomeric type during the translocation process in time as at high enough concentration of BPs, binding events would occur quickly just after the exit of a monomer from the nanopore. The number of chain monomers has been kept at  $N = 128$ , and two cases of multiblock copolymer have been considered here: multiblock copolymers with equal monomeric content  $\text{Poly}(\text{A}_n\text{B}_n)_{N/2n}$  and unequal monomeric content  $\text{Poly}(\text{A}_m\text{B}_n)_{N/(m+n)}$ . Thus, the block length in these two cases is  $M = 2n$  and  $M = m + n$ , respectively. Correspondingly, the number of block gives as  $N/2n$  and  $N/(m + n)$ , respectively.

In the simulations, the motion of a mobile bead is described by the Langevin equation:

$$m\ddot{\mathbf{r}} = -\nabla U_i - \xi \mathbf{v}_i + \mathbf{F}_i^R \quad (4)$$

where  $m$ ,  $\xi$  and  $\mathbf{v}_i$  are the bead's mass, friction coefficient and velocity, respectively.  $-\xi \mathbf{v}_i$  is the frictional force exerted on the bead. The conservative potential  $U_i$  acted on a bead determines the conservative force exerted on it,  $-\nabla U_i$ . Specifically,  $U_i = \sum_{i \neq j} U_{ij}^j + U_{\text{FENE}}(i-1, i, i+1)$  for chain monomers, and  $U_i = \sum_{i \neq j} U_{ij}^j$  for BPs.  $\mathbf{F}_i^R$  is the random force which satisfies the fluctuation-dissipation theorem:<sup>[56]</sup>

$$\begin{aligned} \langle \mathbf{F}_i^R(t) \rangle &= 0, \\ \langle \mathbf{F}_i^R(t) \cdot \mathbf{F}_j^R(t') \rangle &= 2dk_B T \xi \delta_{ij} \delta(t - t') \end{aligned} \quad (5)$$

where  $d$  is the space dimensionality ( $d = 2$  for this work),  $k_B$  is Boltzmann constant,  $\delta_{ij}$  is the Kronecker delta,  $\delta(t - t')$  is the Dirac delta function, and  $T$  is the absolute system temperature. For a dynamics study, how to obtain the movement locus of a bead with the evolution of time is the most concerned. Numerically, the Langevin equation (Eq. 4) is integrated in time in two dimensions by the method proposed by Ermak and Buckholz.<sup>[57]</sup>

Before a translocation try starts, the multiblock copolymer and BPs are under thermal fluctuations described by the Langevin thermostat for a sufficiently long time. In the relaxation process, the first monomer is fixed at the position (1,0) where BPs can bind to it during relaxation. In this way, one can focus on the translocation process itself as the probability of a failed try reduces significantly. Once the relaxation completed, the first monomer is released and a translocation try begins, which is considered to be successful when the last monomer exits the nanopore. One thousand of successful translocation tries have been performed and then data are gathered to extract quantities characterizing the translocation dynamics, such as the mean translocation time  $\langle \tau \rangle$  and the residence time of individual monomers during the translocation  $R(s)$ .

## RESULTS AND DISCUSSION

### Effect of the Block Length on the Translocation

In this section, the multiblock copolymers with an equal monomeric content  $\text{Poly}(\text{A}_n\text{B}_n)_{N/2n}$  is considered. The only variable in this case is the block length  $M = 2n$  ranging from 2 to 128. The main concern here is how the magnitude of  $M$  affects the translocation dynamics. As plotted in Fig. 2(a), an initial increase in the mean translocation time  $\langle \tau \rangle$  with the increasing  $M$  for  $M \leq 16$  is observed. However, for larger block lengths  $M = 32, 64$  and  $128$ ,  $\langle \tau \rangle$  remains nearly unchanged, and approaches

asymptotically the arithmetic average of  $\langle \tau_A \rangle$  and  $\langle \tau_B \rangle$ , i.e.,  $(\langle \tau_A \rangle + \langle \tau_B \rangle)/2$ . Here,  $\langle \tau_A \rangle$  and  $\langle \tau_B \rangle$  is the mean translocation time of homopolymers  $\text{Poly}(\text{A})_{128}$  and  $\text{Poly}(\text{B})_{128}$ , respectively.

The above  $\langle \tau \rangle$ - $M$  behaviors could be interpreted qualitatively in terms of the distribution of energy gain from the binding. Different from homopolymers, the energy gain from the binding of BPs to multiblock copolymers undulates as the translocation proceeds. A smaller block length suggests a more uniform energy gain throughout the overall translocation. Thus, a smaller  $M$  is favorable of the translocation. However, for large  $M$ , the translocation of long blocks with a single species of monomer becomes almost decoupled, and thus the dynamics is not sensitive to  $M$ .

To yield a deeper understanding about the translocation process of a multiblock copolymer, I take a look at the detailed translocation dynamics, i.e., how long a specific monomer takes to get through the nanopore. In the simulations, it can be measured by the residence time of the monomer  $s$ ,  $R(s)$ . The definition of  $R(s)$  is the time interval between the events that the monomer  $s$  and the monomer

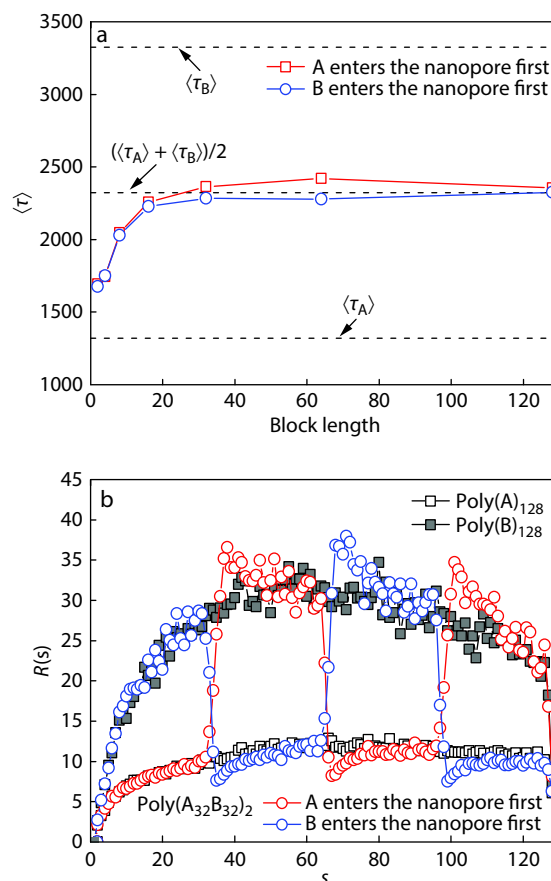


**Fig. 2** (a) The mean translocation time  $\langle \tau \rangle$  as a function of the block length. The lower and upper dashed lines represent the mean translocation time of homopolymers  $\text{Poly}(\text{A})_{128}$  and  $\text{Poly}(\text{B})_{128}$ ,  $\langle \tau_A \rangle$  and  $\langle \tau_B \rangle$ , respectively. The middle dashed line denotes the arithmetic average of  $\langle \tau_A \rangle$  and  $\langle \tau_B \rangle$ , i.e.,  $(\langle \tau_A \rangle + \langle \tau_B \rangle)/2$ . (b) The residence time of the monomer  $s$ ,  $R(s)$  for  $\text{Poly}(\text{A}_{32}\text{B}_{32})_2$  with two different translocation orientations.  $R(s)$  of  $\text{Poly}(\text{A})_{128}$  and  $\text{Poly}(\text{B})_{128}$  are also plotted for comparison.

$s + 1$  get through the nanopore, characterizing the translocation speed of individual monomers. Take the multiblock copolymer  $\text{Poly}(\text{A}_{32}\text{B}_{32})_2$  with the monomer A entering the nanopore first as an example, Fig. 2(b) displays the fluctuations in the translocation speed of individual monomers compared with the homopolymer cases. As the first A-block translocates through the nanopore, for the same  $s$ , the translocation of the first several B-monomers in each B-blocks is significantly slower than that of B-monomers in the homopolymer  $\text{Poly}(\text{B})_{128}$ , while the translocation of the second A-block is slightly faster than that of A-monomers in the homopolymer  $\text{Poly}(\text{A})_{128}$ . This interesting dynamical phenomenon is a direct reflection of the subtle entropic effects induced by the binding: the binding of BPs to the first A-block results in more compact conformations of the translocated A-block, and thus a smaller effective driving force for the first B-block; the effective driving force for the second A-block becomes larger due to the chain conformational entropy increase arising from the weaker binding of BPs with the first B-block.

Similar results have been observed in the case of translocation driven by an electric force applied only inside the nanopore or nanochannels,<sup>[48–50]</sup> which can be explained by the tension propagation (TP) theory.<sup>[58]</sup> That is, the faster translocation of monomers that experience a larger driving force leads to an earlier coupling of monomers at the *cis* side to the translocation process. The increasing viscous drag from the *cis* side is unfavorable for the translocation of monomers that experience a smaller driving force. However, it is noted that the magnitude of fluctuations in  $R(s)$  in this work is smaller than that observed in previous works.<sup>[48–50]</sup> It is mainly attributed to the unique driving mechanism discussed here. The binding of BPs to translocated monomers causes an additional friction for the remaining translocation,<sup>[43,44,46]</sup> and the tension propagation rate along the chain gets reduced. Therefore, the viscous drag from the *cis* side is not as obvious as in the case of electric field driven polymer translocation.<sup>[48–50]</sup>

Since there exist two types of monomeric species in a multiblock copolymer, entrance of the monomer A or the monomer B to the nanopore first might make a difference. Fig. 2(b) also reveals that the entrance orientation determines the detailed translocation dynamics. But, how does the entrance orientation affect the overall translocation dynamics? To measure this effect quantitatively, I define  $\gamma$  as the ratio of the mean translocation time of the monomer A entering the nanopore first to that of the monomer B entering the nanopore first. As shown in Fig. 3,  $\gamma \approx 1$  for all the studied block lengths, suggesting that there is nearly no orientation dependence of the overall translocation dynamics.

A similar observation has been reported for the case of polymer translocation that is driven by an electric field through a nanopore, and the magnitude of the electric force exerted on the monomers depends on their types.<sup>[48]</sup> By comparison, when the monomer species was distinguished by their different attractive strengths with a long nanopore, the entrance orientation did matter,<sup>[49]</sup> leading to  $\gamma > 1$ . The strong dependence of the translocation dynamics on the entrance orientation has also been found in the translocation of polymers consisting of double-stranded blocks and single-stranded blocks,<sup>[53]</sup> and the translocation of amphiphilic polymers.<sup>[59]</sup>

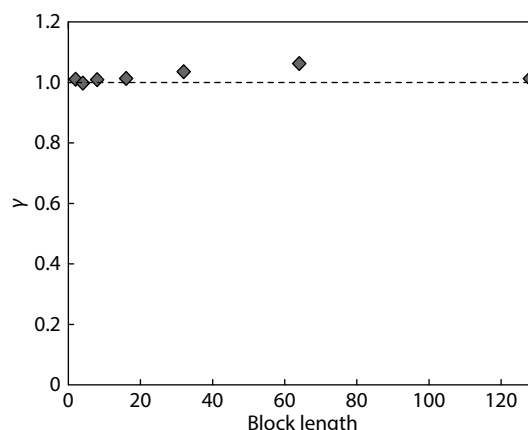


**Fig. 3** The ratio of the mean translocation time  $\langle \tau \rangle$  of the monomer A entering the nanopore first to that of the monomer B entering the nanopore first,  $\gamma$ , as a function of the block length.

The underlying physical reason for the weak or strong dependence of the entrance orientation lies in whether the backward motion of a translocating chain could be suppressed as the entrance orientation changes. In this work, bound BPs could prevent the backsliding of translocated monomers effectively as the size of BPs-monomer complex is larger than that of the nanopore, while frequent backward motions occur when the variation in the entrance orientation was sensed by the setup of previous works.<sup>[49,53,59]</sup>

### Effect of the Monomeric Content on the Translocation

The case of multiblock copolymers with an equal monomeric content  $\text{Poly}(\text{A}_n\text{B}_n)_{N/2n}$  has been studied. Next, I turn the attention to the case of multiblock copolymers with unequal monomeric content  $\text{Poly}(\text{A}_m\text{B}_n)_{N/(m+n)}$  where the content of B-monomers  $f_B = n/(m+n)$  is a variable. Automatically, the concern here is how the translocation dynamics responds to a variation in  $f_B$ .

Fig. 4 shows that with the increasing  $f_B$ ,  $\langle \tau \rangle$  rises due to the weaker binding affinity of BPs with the monomer B, as expected. Interestingly, it is found that the increasing way of  $\langle \tau \rangle$  with  $f_B$  relies on the magnitude of the block length  $M = m + n$ . For small block lengths  $M = 6$  and  $8$ ,  $\langle \tau \rangle$  increases exponentially with an increase in  $f_B$ , i.e.,  $\langle \tau \rangle = \langle \tau_A \rangle e^{f_B}$ . Meanwhile, a nearly linear response of  $\langle \tau \rangle$  to the increasing  $f_B$  has been observed for large block lengths  $M = 32$  and  $64$ , i.e.,  $\langle \tau \rangle = (1 - f_B) \langle \tau_A \rangle + f_B \langle \tau_B \rangle$ . A similar increasing way of  $\langle \tau \rangle$  with  $f_B$  has been found in the case of polymer translocation through a nanopore driven by an electric field, where the decisive factor is whether  $m = 1$  and/or  $n = 1$ .<sup>[48]</sup> By comparison, the decisive factor here is the magnitude of the block length. A qualitative explanation about why  $M$  dominates the increasing way of  $\langle \tau \rangle$  with  $f_B$  will be given shortly afterwards.

### Residence Time for Heterogeneous Polymers

Fig. 2(b) has indicated that for a multiblock copolymer with an equal monomeric content and a large block length, the residence time of individual monomers,  $R(s)$ , could provide rich and detailed information about the translocation dynamics. It is necessary to pay more attentions to  $R(s)$  in more general cases. First, I am curious about whether the present setup is capable of detecting a variation in the monomeric type immediately, as

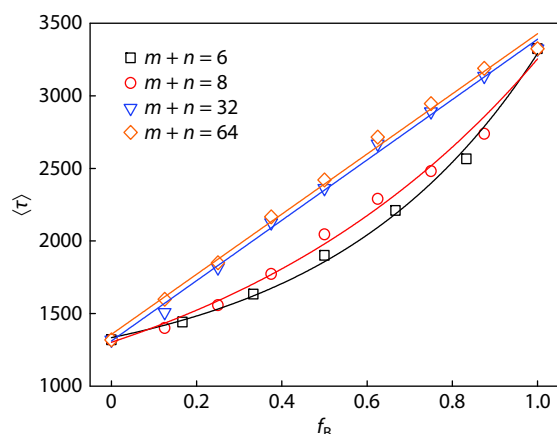


**Fig. 4** Dependence of the mean translocation time  $\langle \tau \rangle$  on the content of the monomer B,  $f_B$ , at four different block lengths,  $m+n=6, 8, 32$ , and  $64$ . The lower two curves (in black and red) and the upper two straight lines (in blue and orange) are the exponential and linear fittings to the data points, respectively. The data drawn here are based on the simulations that the monomer A enters the nanopore first. Data calculated from the simulations that the monomer B enters the nanopore first show the same behaviors, and are thus not plotted for clarity.

has been demonstrated in the case of polymer translocation driven by an electric field.<sup>[50]</sup> To address this question, a multiblock copolymer with the specific sequence structure Poly( $B_{31}AB_{96}$ ) has been designed, and the corresponding  $R(s)$  has been calculated to check whether the translocation dynamics can make a rapid response to the substitution of a monomer B with a monomer A.

As shown in Fig. 5,  $R(s)$  of Poly( $B_{31}AB_{96}$ ) overlaps with that of Poly( $B_{128}$ ) very well at  $s \leq 31$ , i.e., before the substitution (the monomer A with an index  $s=32$ ) exits the nanopore. With the just translocation of the substitution through the nanopore, the stronger binding of BPs to it brings about a larger effective driving force for the translocation of the 33<sup>rd</sup> monomer. Consequently, a much lower  $R(s=32)$  is observed according to the definition of  $R(s)$ . More interestingly, the fastest translocation is achieved for the 34<sup>th</sup> monomer. It might be attributed to the fact that a monomer can bind with several BPs simultaneously. With the proceeding of the translocation, the monomer A would find more free BPs in its vicinity. The allowed multiple bindings of BPs to a monomer benefits the translocation of the 34<sup>th</sup> monomer, and thus a minimum of  $R(s)$  at  $s=33$  is obtained. This speedup effect induced by the substitution would vanish as long as the saturated binding is reached. The overall result of the substitution is the faster translocations of its subsequent 5–6 monomers compared with these in the homopolymer Poly( $B_{128}$ ) with the same sequence indexes  $s$ . Thus, it could be concluded here that BPs-assisted polymer translocation is able to make an immediate response to a variation in the monomeric type. Besides, it should be pointed out that if the binding model is one-to-one as discussed by Suhonen and Linna,<sup>[46]</sup> the speedup effect induced by the substitution should be very weak or even vanished. Here, with the vanishing of the substitution induced speedup effect,  $R(s)$  of Poly( $B_{31}AB_{96}$ ) are in accord with these of Poly( $B_{128}$ ) again for  $s \geq 38$ , as expected.

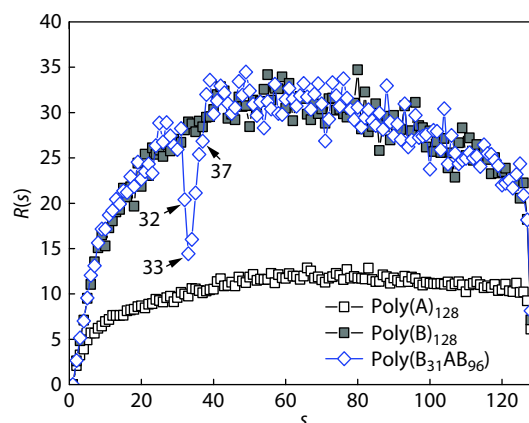


**Fig. 5** Effects of a single monomeric substitution in the homopolymer Poly( $B_{128}$ ) on the detailed translocation dynamics. The residence time of the monomer  $s$ ,  $R(s)$ , for a designed multiblock copolymer with the sequence structure Poly( $B_{31}AB_{96}$ ) is plotted.  $R(s)$  of Poly( $A_{128}$ ) and Poly( $B_{128}$ ) are also plotted for comparison.

The above findings are in favor of the understanding of the observations in Fig. 4. It is reasonable to conjecture that by substituting a monomer B with a monomer A in short blocks, the speedup effect should be quite pronounced in B-rich multiblock copolymers ( $f_B > 0.5$ ). In contrast, the speedup effect would be weaker in A-rich multiblock copolymers ( $f_B < 0.5$ ). This argument explains the exponential increasing of  $\langle \tau \rangle$  with the increasing  $f_B$  qualitatively for multiblock copolymers with short block lengths. Nevertheless, the situation becomes different for multiblock copolymers with large block lengths. In these cases, the whole translocation can be divided into several parts with each part being considered almost independently, as indicated by Fig. 2(b). Therefore, the mean translocation time in the cases of large block lengths makes a linear response to the increasing of  $f_B$ .

Finally, by taking a look back at Fig. 2(b), I find that the periodic structure of a multiblock copolymer leads to a remarkable fingerprint feature in the residence time of individual monomers. There, the number of peaks in  $R(s)$  is exactly equal to the number of blocks  $N/2n$ . However, the fingerprint feature in  $R(s)$  is not a specific example for multiblock copolymer with an equal monomeric content and a large block length, but is common for multiblock copolymers with arbitrary values of  $m$  and  $n$ . Fig. 6 gives the residence time of multiblock polymers Poly( $AB_7$ )<sub>16</sub> and Poly( $A_{10}B_6$ )<sub>8</sub>. It is readily found that the number of peaks in the corresponding  $R(s)$  is exactly equal to the number of blocks  $N/(m+n) = 16$  and  $8$ , respectively.

The fingerprint feature in the residence time of individual monomers might imply that if  $R(s)$  could be determined accurately from experiments, it would allow one to identify the structural information of translocated multiblock copolymers. As well known, the identification of bases is usually by reading the ionic current signal variations in DNA-sequencing experiments.<sup>[2]</sup> Yet, there is no ionic current signal variations during the translocation in the setup of this work. Although how to put the fingerprint feature of the residence time into practical use remains a huge challenge, this work puts forward a possibility of utilizing BPs-assisted translocation to se-

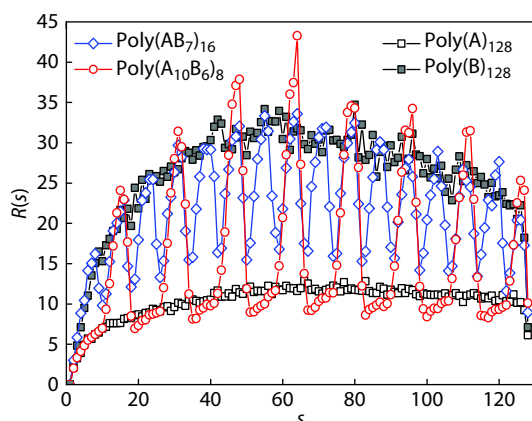


**Fig. 6** The residence time of multiblock copolymers Poly( $AB_7$ )<sub>16</sub> and Poly( $A_{10}B_6$ )<sub>8</sub>. Here, only the cases that the monomer A enters the nanopore first are plotted.  $R(s)$  of Poly( $A$ )<sub>128</sub> and Poly( $B$ )<sub>128</sub> are drawn to guide the eye.

quence heterogeneous polymers or proteins.

## CONCLUSIONS

In summary, I have investigated the translocation dynamics of heterogeneous flexible polymers through a nanopore assisted by binding particles by using the coarse-grained Langevin dynamics simulations. For multiblock copolymers with an equal monomeric content Poly( $A_nB_n$ ) <sub>$N/2n$</sub> , it has been shown that as the block length  $M$  rises, the mean translocation time  $\langle\tau\rangle$  increases for small block lengths ( $M \leq 16$  in this work), and remains nearly unchanged for larger block lengths ( $M \geq 32$  in this work). Besides, the translocation dynamics hardly depends on the entrance orientation. For multiblock copolymers with a unequal monomeric content Poly( $A_mB_n$ ) <sub>$N/(m+n)$</sub> , how  $\langle\tau\rangle$  increases with an increase in the content of the monomer B is up to the magnitude of block length: a crossover from an exponential increase at small  $M$  to a linear increase at large  $M$  has been found.

It has been demonstrated that the present setup can capture the variations in the type of monomer that just exits the nanopore. Due to the multiple binding of BPs to a monomer, even one substitution in a homopolymer occurs, the speedup effect for the translocation of the subsequent several monomers is quite evident. Finally, it has been revealed that the periodic structure of a multiblock copolymer leads to a remarkable fingerprint feature in the residence time of individual monomers. I believe that the present work constructs a relationship between the translocation dynamics and the sequence structure for multiblock copolymers. From the perspective of polymer sequencing, the translocation of heterogeneous polymers with multiple types of monomer and/or random sequence is the more general case, and remains to be studied in the future.

## ACKNOWLEDGMENTS

This work was financially supported by the China Postdoctoral Science Foundation (No. 2015M581998).

## REFERENCES

- Alberts, B.; Johnson, A.; Lewis, J.; Raff, M.; Roberts, K.; Walter, P. *Molecular biology of the cell*. 5<sup>th</sup> Ed. Garland Science, New York, **2007**.
- Kasianowicz, J. J.; Brandin, E.; Branton, D.; Deamer, D. W. Characterization of individual polynucleotide molecules using a membrane channel. *Proc. Natl. Acad. Sci. U.S.A.* **1996**, *93*, 13770–13773.
- Bayley, H. Sequencing single molecules of DNA. *Curr. Opin. Chem. Biol.* **2006**, *10*, 628–637.
- Sun, T.; Ma, H.; Deng, S. Translocation of a protein-like chain through an interacting channel. *Chinese J. Polym. Sci.* **2011**, *29*, 520–531.
- de Haan, H. W.; Slater, G. W. Translocation of “rod-coil” polymers: probing the structure of single molecules within nanopores. *Phys. Rev. Lett.* **2013**, *110*, 048101.
- Sun, L.; Li, H.; Xu, X.; Luo, M. Simulation study on the translocation of polyelectrolyte through conical nanopores. *J. Phys.: Condens. Matter* **2018**, *30*, 495101.
- Sun, L.; Wang, C.; Luo, M.; Li, H. Trapped and non-trapped polymer translocations through a spherical pore. *J. Chem. Phys.* **2019**, *150*, 024904.
- Huopaniemi, I.; Luo, K.; Ala-Nissila, T.; Ying, S. C. Polymer translocation through a nanopore under a pulling force. *Phys. Rev. E* **2007**, *75*, 061912.
- de Haan, H. W.; Sean, D.; Slater, G. W. Reducing the variance in the translocation times by prestretching the polymer. *Phys. Rev. E* **2018**, *98*, 022501.
- Guo, J.; Li, X.; Liu, Y.; Liang, H. Flow-induced translocation of polymers through a fluidic channel: a dissipative particle dynamics simulation study. *J. Chem. Phys.* **2011**, *134*, 134906.
- Li, X.; Pivkin, I. V.; Liang, H. Hydrodynamic effects on flow-induced polymer translocation through a microfluidic channel. *Polymer* **2013**, *54*, 4309–4317.
- Ding, M.; Duan, X.; Shi, T. Flow-induced polymer separation through a nanopore: effects of solvent quality. *Soft Matter* **2017**, *13*, 7239–7243.
- He, J.; Zheng, T.; Li, L. Study of flow-driven translocation of flexible polymer chains through cylindrical nanopores in unentangled semidilute solutions. *Macromolecules* **2019**, *52*, 5679–5689.
- Milchev, A.; Binder, K.; Bhattacharya, A. Polymer translocation through a nanopore induced by adsorption: Monte Carlo simulation of a coarse-grained model. *J. Chem. Phys.* **2004**, *121*, 6042–6051.
- Yang, S.; Neimark, A. V. Adsorption-driven translocation of polymer chain into nanopores. *J. Chem. Phys.* **2012**, *136*, 214901.
- Zhao, X.; Yu, W.; Luo, K. Surface-adsorption-induced polymer translocation through a nanopore: effects of the adsorption strength and the surface corrugation. *Phys. Rev. E* **2015**, *92*, 022603.
- Wei, D.; Yang, W.; Jin, X.; Liao, Q. Unforced translocation of a polymer chain through a nanopore: the solvent effect. *J. Chem. Phys.* **2007**, *126*, 204901.
- Lörscher, C.; Ala-Nissila, T.; Bhattacharya, A. Polymer translocation induced by a bad solvent. *Phys. Rev. E* **2011**, *83*, 011914.
- Moisio, J. E.; Piili, J.; Linna, R. P. Driven polymer translocation in good and bad solvent: effects of hydrodynamics and tension propagation. *Phys. Rev. E* **2016**, *94*, 022501.
- Matlack, K. E. S.; Mothes, W.; Rapoport, T. A. Protein translocation: tunnel vision. *Cell* **1998**, *92*, 381–390.
- Matlack, K. E. S.; Misselwitz, B.; Plath, K.; Rapoport, T. A. BiP acts as a molecular ratchet during posttranslational transport of prepro- $\alpha$  factor across the ER membrane. *Cell* **1999**, *97*, 553–564.

- 22 Neupert, W.; Brunner, M. The protein import motor of mitochondria. *Nat. Rev. Mol. Cell. Biol.* **2002**, 3, 555–565.
- 23 Salman, H.; Zbaida, D.; Rabin, Y.; Chatenay, D.; Elbaum, M. Kinetics and mechanism of DNA uptake into the cell nucleus. *Proc. Natl. Acad. Sci. U.S.A.* **2001**, 98, 7247–7252.
- 24 Farkas, K.; Derényi, I.; Vicsek, T. DNA uptake into nuclei: numerical and analytical results. *J. Phys.: Condens. Matter* **2003**, 15, S1767–S1777.
- 25 Simon, S. M.; Peskin, C. S.; Oster, G. F. What drives the translocation of proteins? *Proc. Natl. Acad. Sci. U.S.A.* **1992**, 89, 3770–3774.
- 26 Peskin, C. S.; Simon, S. M.; Oster, G. F. Cellular motions and thermal fluctuations: the Brownian ratchet. *Biophys. J.* **1993**, 65, 316–324.
- 27 Liebermeister, W.; Rapoport, T. A.; Heinrich, R. Ratcheting in post-translational protein translocation: a mathematical model. *J. Mol. Biol.* **2001**, 305, 643–656.
- 28 Elston, T. C. Models of post-translational protein translocation. *Biophys. J.* **2000**, 79, 2235–2251.
- 29 Elston, T. C. The Brownian ratchet and power stroke models for posttranslational protein translocation into the endoplasmic reticulum. *Biophys. J.* **2002**, 82, 1239–1253.
- 30 Zandi, R.; Reguera, D.; Rudnick, J.; Gelbart, W. M. What drives the translocation of stiff chains? *Proc. Natl. Acad. Sci. U.S.A.* **2003**, 100, 8649–8653.
- 31 Ambjörnsson, T.; Metzler, R. Chaperone-assisted translocation. *Phys. Biol.* **2004**, 1, 77–88.
- 32 Ambjörnsson, T.; Lomholt, M. A.; Metzler, R. Directed motion emerging from two coupled random processes: translocation of a chain through a membrane nanopore driven by binding proteins. *J. Phys.: Condens. Matter* **2005**, 17, S3945–S3964.
- 33 D'Orsogna, M. R.; Chou, T.; Antal, T. Exact steady-state velocity of ratchets driven by random sequential adsorption. *J. Phys. A: Math. Theor.* **2007**, 40, 5575–5584.
- 34 Krapivsky, P. L.; Mallick, K. Fluctuations in polymer translocation. *J. Stat. Mech.* **2010**, 7, P07007.
- 35 Abdolvahab, R. H.; Roshani, F.; Nourmohammad, A.; Sahimi, M.; Tabar, M. R. R. Analytical and numerical studies of sequence dependence of passage times for translocation of heterobiopolymers through nanopores. *J. Chem. Phys.* **2008**, 129, 235102.
- 36 Abdolvahab, R. H.; Ejtehadi, M. R.; Metzler, R. Sequence dependence of the binding energy in chaperone-driven polymer translocation through a nanopore. *Phys. Rev. E* **2011**, 83, 011902.
- 37 Abdolvahab, R. H.; Metzler, R.; Ejtehadi, M. R. First passage time distribution of chaperone driven polymer translocation through a nanopore: homopolymer and heteropolymer cases. *J. Chem. Phys.* **2011**, 135, 245102.
- 38 Yu, W.; Ma, Y.; Luo, K. Translocation of stiff polymers through a nanopore driven by binding particles. *J. Chem. Phys.* **2012**, 137, 244905.
- 39 Abdolvahab, R. H. Investigating binding particles distribution effects on polymer translocation through nanopore. *Phys. Lett. A* **2016**, 380, 1023–1030.
- 40 Abdolvahab, R. H. Chaperone-driven polymer translocation through nanopore: spatial distribution and binding energy. *Eur. Phys. J. E* **2017**, 40, 41.
- 41 Abdolvahab, R. H. Non-equilibrium effects in chaperone-assisted translocation of a stiff polymer. *Phys. Lett. A* **2018**, 382, 162–167.
- 42 Uhl, M.; Seifert, U. Force-dependent diffusion coefficient of molecular Brownian ratchets. *Phys. Rev. E* **2018**, 98, 022402.
- 43 Yu, W.; Luo, K. Chaperone-assisted translocation of a polymer through a nanopore. *J. Am. Chem. Soc.* **2011**, 133, 13565–13570.
- 44 Yu, W.; Luo, K. Polymer translocation through a nanopore driven by binding particles: influence of chain rigidity. *Phys. Rev. E* **2014**, 90, 042708.
- 45 Adhikari, R.; Bhattacharya, A. Translocation of a semiflexible polymer through a nanopore in the presence of attractive binding particles. *Phys. Rev. E* **2015**, 92, 032711.
- 46 Suhonen, P. M.; Linna, R. P. Chaperone-assisted translocation of flexible polymers in three dimensions. *Phys. Rev. E* **2016**, 93, 012406.
- 47 Emamyari, S.; Fazli, H. Polymer translocation through a nanopore in the presence of chaperones: a three dimensional MD simulation study. *Comput. Condens. Matter* **2017**, 13, 96–103.
- 48 Luo, K.; Ala-Nissila, T.; Ying, S. C.; Bhattacharya, A. Heteropolymer translocation through nanopores. *J. Chem. Phys.* **2007**, 126, 145101.
- 49 Luo, K.; Ala-Nissila, T.; Ying, S. C.; Bhattacharya, A. Sequence dependence of DNA translocation through a nanopore. *Phys. Rev. Lett.* **2008**, 100, 058101.
- 50 Luo, K.; Ala-Nissila, T.; Ying, S. C.; Bhattacharya, A. Dynamics of DNA translocation through an attractive nanopore. *Phys. Rev. E* **2008**, 78, 061911.
- 51 Gauthier, M. G.; Slater, G. W. Sequence effects on the forced translocation of heteropolymers through a small channel. *J. Chem. Phys.* **2008**, 128, 175103.
- 52 Mirigian, S.; Wang, Y.; Muthukumar, M. Translocation of a heterogeneous polymer. *J. Chem. Phys.* **2012**, 137, 064904.
- 53 Kotsev, S.; Kolomeisky, A. B. Effect of orientation in translocation of polymers through nanopores. *J. Chem. Phys.* **2006**, 125, 084906.
- 54 Kumar, R.; Chaudhuri, A.; Kapri, R. Sequencing of semiflexible polymers of varying bending rigidity using patterned pores. *J. Chem. Phys.* **2018**, 148, 164901.
- 55 Kremer, K.; Grest, G. S. Dynamics of entangled linear polymer melts: a molecular-dynamics simulation. *J. Chem. Phys.* **1990**, 92, 5057–5086.
- 56 Chandler, D. *Introduction to modern statistical mechanics*. Oxford University Press, USA, **1987**.
- 57 Ermak, D. L.; Buckholz, H. Numerical integration of the Langevin equation: Monte Carlo simulation. *J. Comput. Phys.* **1980**, 35, 169–182.
- 58 Sakaue, T. Nonequilibrium dynamics of polymer translocation and straightening. *Phys. Rev. E* **2007**, 76, 021803.
- 59 Tsuchiya, S.; Matsuyama, A. Translocation and insertion of an amphiphilic polymer. *Phys. Rev. E* **2007**, 76, 011801.