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Mimicking the regulatory state of a major facilitator superfamily sugar transporter

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Abstract

While many 3D structures of cation-coupled transporters have been determined, the mechanistic details governing the obligatory coupling and functional regulations still remain elusive. The bacterial melibiose transporter (MelB) is a prototype of the Na^+-coupled major facilitator superfamily transporters. With a conformational nanobody (Nb), we determined an inward-facing Na^+-bound, low-sugar affinity cryoEM structure. It is the first structure of a major facilitator superfamily (MFS) transporter with experimentally determined cation binding, and also a structure mimicking the physiological regulatory state of MelB under the global regulator $EIIA^{Glc}$ of the glucose-specific phosphoenolpyruvate:phosphotransferase system. Collectively with the available outward-facing sugar-bound structures and a large body of functional analysis, we identified that only inner barrier that exists in the outward-facing conformation contributes to the sugar selectivity pocket. When the inner barrier is broken as shown in the inward-facing conformation, the sugar selectivity pocket is also broken, resulting in a decreased sugar-binding affinity by greater than 30-fold, which can facilitate the substrate release and accumulation intracellularly. The inner/outer barrier shifting directly regulates the sugar-binding affinity, with no effect on the cation binding as also suggested by molecular dynamics simulations. Furthermore, the use of the inward-facing conformation-specific Nb in combination with the hydron/deuterium exchange mass spectrometry allowed us to identify dynamic regions linked to the inner barrier-specific charged network and critical for the barrier switching mechanisms. The complementary results provided structural, dynamic, and regulatory insights into the mobile barrier mechanism for cation-coupled symport.

eLife assessment

In a **valuable** study that will be of interest to the mechanistic membrane transport community, the authors capture the first cryo-EM structure of the inward facing melbiose transporter MelB, a well-studied model transporter from the major facilitator (MFS) superfamily. Cryo-EM experiments and supporting biophysical experiments provide **solid** evidence for transporter conformational changes. The supporting evidence is **incomplete** in that the maps were not provided for review.

Introduction

Cation-coupled transporters play critical roles in many aspects of cell physiology and pharmacokinetics and are involved in many serious diseases including cancers, metabolic diseases, neurodegenerative diseases, etc. Their specific locations and functions make them viable drug targets[1,2]. Following decades of effort, the structures of many transporters have been determined by x-ray crystallography and, more recently, by cryoEM[3–14]. However, we still do not have a deep understanding of the structural basis for substrate accumulation to high concentrations, the mechanisms for the obligatorily coupled transport, as well as the cellular regulation of transporters' activities to meet metabolic needs.

Salmonella enterica serovar Typhimurium melibiose permease ($MelB_{St}$) is the prototype Na^+/solute transporter of the major facilitator superfamilies (MFS)[11,15–24]. It catalyzes the stoichiometric symport of galactopyranoside with Na^+, H^+, or Li^+[25]. Crystal structures of sugar-bound states have been determined, which reveals the sugar recognition mechanism[19]. In all solved x-ray crystal structures, $MelB_{St}$ is in an outward-facing conformation; the observed physical barrier of the sugar translocation, named the inner barrier, prevents the substrate from moving into the cytoplasm directly (see **Fig. 4b**). It is well-known that transporters change their conformation to allow the substrate translocation from one side of the membrane to the other and conformational dynamics is the intrinsic feature necessary for their functions[3,6,7,12,13,26,27].

To understand how the substrate dictates transporter function, we have established thermodynamic binding cycles in $MelB_{St}$ using isothermal titration calorimetry (ITC) measurements and identified that the positive cooperativity of the binding of cation and melibiose[17]; furthermore, the binding of the second substrate changes the thermodynamic feature of heat capacity change from positive to negative, suggesting primary dehydration processes when both substrates concurrently occupy the transporter[28]. While the structural origins have not yet been completely determined yet, they may be related to forming an occluded intermediate conformation, a necessary state for a global conformational transition.

To determine structurally unresolved states of $MelB_{St}$, nanobodies (Nbs) were raised against the wild-type $MelB_{St}$. One group of Nbs (Nb714, Nb725, and Nb733) has been identified to interact with the cytoplasmic side of $MelB_{St}$ and their binding completely inhibits $MelB_{St}$ transport activity[29]. $MelB_{St}$ bound with Nb725 or Nb733 retained its binding to Na^+, but its affinity for melibiose is inhibited. The $MelB_{St}$/Nb733 complex also retained the affinity to its physiological regulator dephosphorylated $EIIA^{Glc}$ of the glucose-specific phosphoenolpyruvate:phosphotransferase system (PTS). $EIIA^{Glc}$, the central metabolite regulator in bacterial catabolic repression[30–32], greatly inhibited the galactoside binding to non-PTS permeases MelB [33]and the H^+-coupled lactose permease (LacY)[34], but still retained the binding of Na^+ to MelB [29]. Thus, the functional modulation of the two Nbs on MelB mimics the binding of $EIIA^{Glc}$. The crystal structure of

dephosphorylated $EIIA^{Glc}$ binding to the maltose permease $MalFGK_2$, an ATP-binding cassette transporter, has been determined[35], but there is no structural information on $EIIA^{Glc}$ binding to the MFS transporters. Determination of the structures of $MelB_{St}$ in complex with this group of Nbs is important and will reveal critical information to understand the manner by which $EIIA^{Glc}$ regulates the large group of MFS sugar transporters.

In the current study, we applied cryoEM single-particle analysis (cryoEM-SPA) and determined the near-atomic resolution structure of $MelB_{St}$ complexed with a Nb725_4, a modified Nb725 with a designed scaffold which enables NabFab binding[36]. The use of the Nb provided a Na^+-bound lower sugar-affinity inward-facing conformation of $MelB_{St}$. Furthermor, our studies using this conformation-selective Nb in combination with hydrogen/deuterium exchange mass spectrometry (HDX-MS) demonstrate a powerful approach for characterizing protein conformational flexibility[37,38], and also provides critical dynamic information to understand how the substrate binding drives the conformational transition necessary for the substrate translocation in $MelB_{St}$.

Results

CDR grafting to generate a hybrid Nb and its functional characterization

To facilitate structure determination of $MelB_{St}$ complexed with the conformation selective Nb by cryoEM-SPA, a novel universal tool based on a NabFab was applied to increase the effective mass of small particles[36], since $MelB_{St}$ (mass, 53.5 kDa) has limited extramembrane mass. A hybrid Nb725_4 was created by CDR grafting[39] to transfer the binding specificity of $MelB_{St}$ Nb725 to the TC-Nb4 recognized by the NabFab[36] (**sFig. 1**). Extensive *in vivo* and *in vitro* functional characterization revealed that the hybrid Nb725_4 possesses the binding properties of its parents Nbs (Nb725 and TC-Nb41) with slightly compromised affinities to $MelB_{St}$.

The *E. coli* cell-based cAMP-dependent two-hybrid T18/T25 assay showed that the two hybrids of Nb725 4:T18 and T25:$MelB_{St}$ reconstituted adenylyl cyclase activities (**Fig. 1a**), which behaved similarly to the parent fusion Nb725:T18[29]. The co-expression of either of the Nbs with $MelB_{St}$ inhibited MelB-mediated melibiose fermentation and transport (**Fig. 1 b&c**). The data confirmed the cytoplasmic interaction of both Nbs in *E. coli* cells. *In vitro* ITC measurements showed that Nb725_4 slightly reduced affinity to $MelB_{St}$ at an equilibrium dissociation constant (K_d) of 3.64 ± 0.62 μM, compared to 1.58 ± 0.42 μM for Nb725 (**Fig. 1d**; **Table 1**). The parent Nb725 had a poor binding to the NabFab (**sFig. 1b**), but Nb725_4 exhibited greatly increased affinity to NabFab at a K_d value of 52.53 ± 13.03 nM (**Fig. 1c**; **Table 1**). The anti-Fab Nb binding to NabFab was two-fold poorer than Nb725_4 at a K_d value of 0.11 ± 0.16 μM (**sFig. 1d; Table 1**). The complex containing all four proteins including $MelB_{St}$, Nb725_4, NabFab, and anti-Fab Nb showed shift peak-shift in the gel-filtration chromatography (**sFig. 1e**).

Nb275_4 binding properties were further analyzed in the presence of the MelB ligands. As expected, the presence of melibiose yielded 6- and 3-fold inhibition, and α-NPG afforded 8- and 4-fold inhibition, on the binding of Nb725 and Nb725_4, respectively (**Table 1**; **sFig. 2**). The physiological regulatory protein $EIIA^{Glc}$ (**Table 1**; **sFig. 2)** showed no inhibition on the binding affinity of both Nbs.

Various ligands binding to the Nb/$MelB_{St}$ complex in the presence of Na^+ were also examined with ITC. As published[29], the melibiose binding was not detectable in the presence of Nb725 (s**Fig. 3a**). To characterize the sugar effect quantitatively, the α-NPG binding was carried out. Interestingly, the exothermic binding observed in the absence of the Nb changed to endothermic binding reactions in the Nb-bound states. Also, affinity affinities decreased by 21~32- for both Nbs

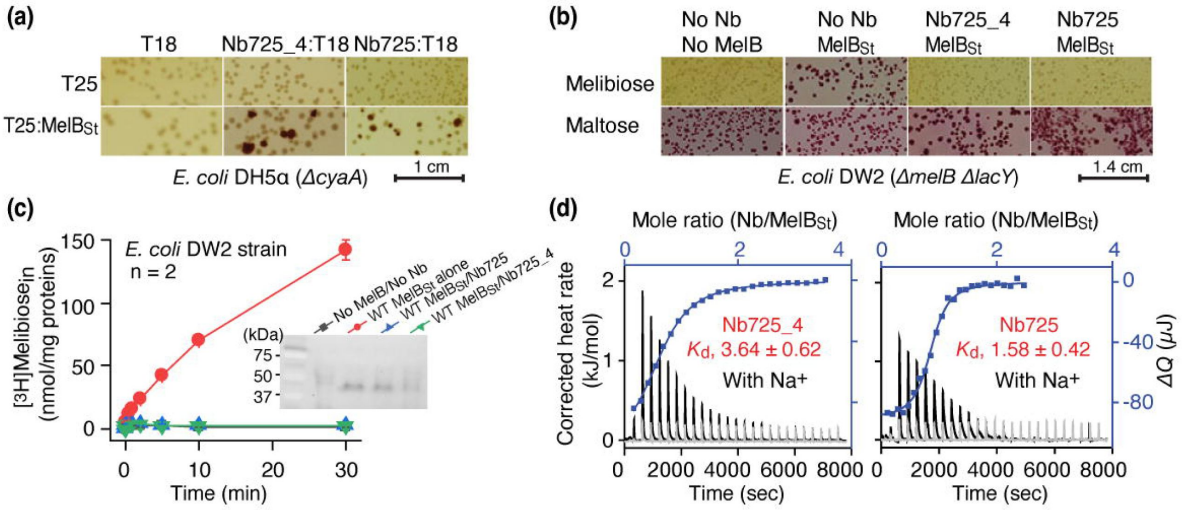

Fig. 1.

Functional characterization of the hybrid Nb725_4.

(a) *In vivo* two-hybrid interaction assay. The test was performed in *E. coli* DH5α *cyaA* cells on the maltose-containing MacConkey agar plate as described in Methods. When the T18 and T25 fragments encoded by two compatible plasmids were expressed separately, or only one fusion of either T25:$MelB_{St}$ or Nbs:T18, no cAMP was produced, so no maltose fermentation was observed as shown in yellow colonies. The interaction of two hybrid proteins of T25:$MelB_{St}$ and Nbs:T18 restored adenylate cyclase activities and cAMP production, which resulted in sugar fermentation. The irregular red colonies are typical of a positive two-hybrid test. **(b)** Nb inhibition of melibiose fermentation. Two compatible plasmids encoding $MelB_{St}$ and Nb725 or Nb725_4 were transformed into *E. coli* DW2 cells [Δ*melB*Δ*lacYZ*] and plated on the MacConkey agar plate containing maltose (as the positive control) and melibiose (indicating melibiose transport activity of $MelB_{St}$) as the sole carbon source. **(c)** [^{3}H]Melibiose transport assay with *E. coli* DW2 cells. The cells transformed by two compatible plasmids encoding the $MelB_{St}$ and Nb725 or Nb725_4 were prepared for [^{3}H]melibiose transport assay at 0.4 mM (specific activity of 10 mCi/mmol) and 20 mM Na^+ as described in Methods. The cells transformed with the two empty plasmids without MelB or Nb were the negative control. **Inset**, Western blot. $MelB_{St}$ expression under the co-expression system was analyzed by isolating the membrane fractions. An Aliquot of 50 μg was loaded on each well and $MelB_{St}$ protein was probed by anti-His antibody. **(d)** Nb binding to $MelB_{St}$ by ITC measurements. As described in Methods, the thermograms were collected with the Nano-ITC device (TA Instrument) at 25 °C. Purified Nbs and $MelB_{St}$ protein samples were dialyzed against 20 mM Tris-HCl, pH 7.5, 100 mM NaCl, 0.01% DDM, and 10% glycerol. Exothermic thermograms were obtained by titrating Nbs (0.3 mM) into the $MelB_{St}$-free buffer (gray) or $MelB_{St}$ (35 mM)-containing buffer (black) in the Sample Cell and plotted using bottom/left (x/y) axes. The binding isotherm and fitting of the mole ratio (Nb/$MelB_{St}$) vs. the total heat change (Δ*Q*) using one-site independent-binding model were presented by top/right (x/y) axes. The dissociation constant K_d was presented at mean ± SEM (number of tests = 6-7).

Titrant	Titrate condition	K_d (μM)	Number of tests	Fold of affinity change	P^
Nb725_4	$MelB_{St}/Na^+$	3.64 ± 0.62*	7		
	$MelB_{St}/Na^+$/Melibiose	11.81 ± 0.72	6	- 3.24	< 0.01
	$MelB_{St}/Na^+$/αNPG	14.63 ± 1.27	2	- 4.02	< 0.01
	$MelB_{St}/Na^+/EIIA^{Glc}$	2.14 ± 0.11	2	+ 1.70	> 0.05
	NabFab	52.53 ± 13.03$	2		
Nb725	$MelB_{St}/Na^+$	1.58 ± 0.42	6		
	$MelB_{St}/Na^+$/Melibiose	8.88 ± 1.24	5	- 5.62	< 0.01
	$MelB_{St}/Na^+$/αNPG	12.58 ± 0.60	2	- 7.96	< 0.01
	$MelB_{St}/Na^+/EIIA^{Glc}$	1.18 ± 0.12	2	+ 1.34	> 0.05
	NabFab	36.02	1		
Anti-Fab Nb	NabFab	0.12 ± 0.02	2		

^ Unpaired *t* test.
* mean ± sem.
$ nM

Table 1.

Nbs binding

(**Table 2**; **sFig. 3b**). Inhibitions of galactosides have been observed in the case of $EIIA^{Glc}$/$MelB_{St}$ complex[33,34]. Collectively, galactosides binding to $MelB_{St}$ were mutually exclusive with Nbs (Nb725, Nb725_4, or Nb733) or $EIIA^{Glc}$, and the negative cooperativity implied that $MelB_{St}$ conformations favored by galactosides and those binders differ. This conclusion was further supported by the Na^+ or $EIIA^{Glc}$ binding to the $MelB_{St}$/Nb complexes (**Table 2; sFig. 3c-d)**, which showed no inhibition for Na^+ affinity and even slightly better binding for $EIIA^{Glc}$. Therefore, $MelB_{St}$ complexed with Nb725_4 retains its physiological functions, and its conformation is expected to be similar when trapped by either of those binders but is different from the sugar-bound outward-facing structure [PDB ID 7L17][19].

Inward-facing $MelB_{St}$ trapped by Nb725_4

CryoEM-SPA was used to image the complex consisting of $MelB_{St}$ in nanodiscs, Nb725_4, NabFab, and anti-Fab Nb. The data collection, processing, and evaluation followed the standard protocols **(sFigs. 4-5)**. From a total number of 296,925 selected particles, structures of $MelB_{St}$, Nb725_4, and NabFab were determined to a golden standard Fourier shell correlation (GSFSC) resolution of 3.29 Å at 0.143 (**Fig. 2**) [PDB ID 8T60]. The map for anti-Fab Nb were relatively poor and excluded from particle reconstruction. The quality of the Coulomb potential map allowed for unambiguous docking of available coordinates of NabFab [PDB ID 7PHP], a predicted model for Nb725_4 by Alpha-Fold 2[40,41], and the N-terminal helix bundle from the outward-facing crystal structure of D59C $MelB_{St}$ [PDB ID 7L17]. The C-terminal helix bundle of $MelB_{St}$ and the ion Na^+ were manually built. The final model contains 417 $MelB_{St}$ residues (positions 2-210, 219-355, and 364-432), with 6 unassigned side-chains at the C-terminal domain (Leu293, Tyr355, Arg363, Tyr369, Tyr396, and Met410) due to the map disorder, 122 of Nb725_4 residues 2-123, and 229 of NabFab H-chain residues 1-214, and 210 of NabFab L-chain residues 4-213, respectively. The local resolution estimate showed that the cores of NabFab, Nb725_4, and the N-terminal helix bundle of $MelB_{St}$ exhibit better resolutions up to 2.84 Å and most regions in the C-terminal helix bundle of $MelB_{St}$ have resolutions between 3.2 to 3.6 Å (**sFig. 6a**). The N-terminal helix bundle has a completely connected density; however, the map corresponding to three cytoplasmic loops at positions 211-218 in the middle $loop_{6\text{-}7}$, positions 356-361 in $loop_{10\text{-}11}$, or the entire C-terminal tail after Tyr432, is missing. The map quality, model statistics, and the model-map matching *Q* scores, generally matched to this reporting resolution (**Supplementary sTable 1; sFig. 6a-c).**

The NabFab structure in this complex is virtually identical to that in the NorM complex [PDB ID 7PHP][36] with rmsd of all atoms of 1.334 Å (**sFig. 7a-c**). When the alignment focused on the NabFab H-chain, the two NabFab/Nb binary complexes in both complexes were organized similarly (**sFig. 7d)**, and the binding of Nbs with their corresponding transporters varied.

The structure shows that the Nb725_4 is bound to the cytoplasmic side of $MelB_{St}$ at an inward-open conformation (**sFig. 8a&b)**, which supports the functional analyses and reveals the $MelB_{St}$ conformation for the Nb binding. The contact surfaces match in shape and surface potential with a contact area of 435 A^2. CDR-1 (Arg30, Asp31, Asn32, and Ala33) and CDR-2 (Tyr52, Asp53, Lue54, Tyr56, Thr57, and Ala58) form interactions with two cytoplasmic regions of $MelB_{St}$, the tip between helices IV and V, i.e., $loop_{4\text{-}5}$, (Pro132, Thr133, Asp137, Lys138, and Arg141) and the beginning region of the middle $loop_{6\text{-}7}$ (Tyr205, Ser206, and Ser207) (**sFig. 8c**). The Nb binding was stabilized by salt-bridge and hydrogen-bonding interactions at both corners of this stretch of inter-protein contacts. In the published outward-open conformation of $MelB_{St}$, such a binding surface for recognizing Nb725_4 does not exist. Most regions of the middle loop, the C-terminal helix bundle, and the C-terminal tail helix must be displaced to permit the binding, and some of those regions are completely disordered in this inward-facing structure. All data supported that Nb725_4 only binds to $MelB_{St}$ at an inward-open state. Since this Nb, its parent Nb725, and another Nb733[29] behave similarly, and all inhibit the sugar binding and transport, we conclude that all three binders are the inward-facing conformation-specific negative modulators of $MelB_{St}$. Further, ITC measurements (**sFig. 2**) also showed that $MelB_{St}$ binds to either of three Nbs in the absence or

Titrant	Titrate condition	K_d (μM)	Number of tests	Fold of affinity change	P^
Melibiose	$MelB_{St}/Na^+$	1,430 ± 30.0*	5	/	
	$MelB_{St}/Na^+$/Nb725_4	/#	3		
	$MelB_{St}/Na^+$/Nb725	/	3		
αNPG	$MelB_{St}/Na^+$	16.46 ± 0.21	5	/	
	$MelB_{St}/Na^+$/Nb725_4	531.55 ± 19.25	2	- 32.29	< 0.01
	$MelB_{St}/Na^+$/Nb725	353.55 ± 37.25	2	- 21.48	< 0.01
Na^+	$MelB_{St}$	261.77 ± 49.15	4	/	
	$MelB_{St}$/Nb725_4	345.04 ± 9.92	2	- 1.32	> 0.05
	$MelB_{St}$/Nb725	182.50 ± 11.30	2	+ 1.43	> 0.05
$EIIA^{Glc}$	$MelB_{St}/Na^+$	3.76 ± 0.29	5	/	
	$MelB_{St}/Na^+$/Nb725_4	4.32 ± 0.64	4	- 1.15	> 0.05
	$MelB_{St}/Na^+$/Nb725	1.94 ± 0.10	4	+ 1.94	< 0.01

* mean ± sem.
# not detectable.
^ Unparied *t* test.

Table 2.

Nb effects on $MelB_{St}$ binding to sugar, Na^+ and $EIIA^{Glc}$

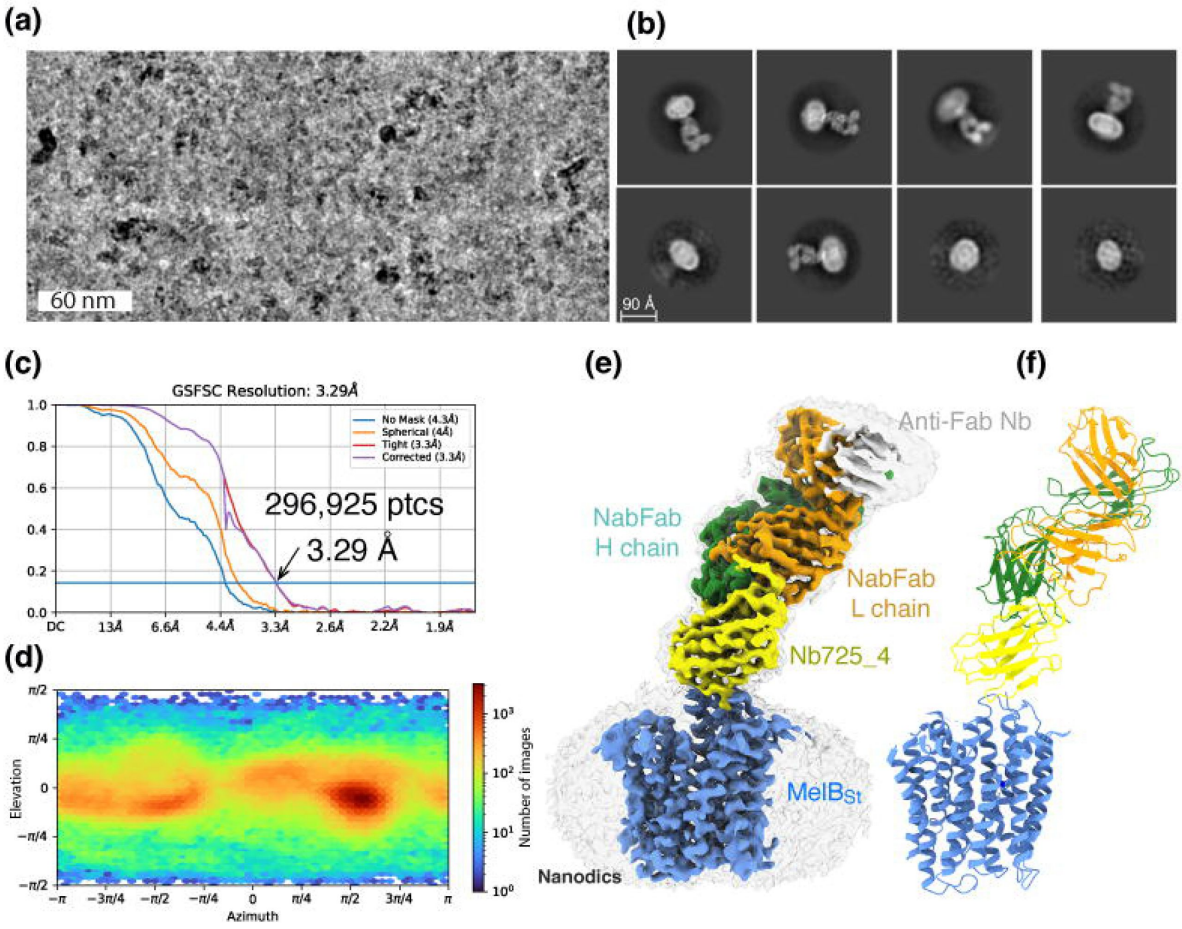

Fig. 2.

CryoEM-SPA.

The sample containing the wild-type $MelB_{St}$ in lipids nanodiscs, the MelB- specific Nb725_4, NabFab, and anti-Fab Nb at 1.5 mg/ml in 20 mM Tris-HCl, pH 7.5, and 150 mM NaCl was prepared as described in the Methods. Images were collected using Titan Krios TEM with a K3 detector of S^2C^2, Stanford, CA. The particle reconstructions and modeling were performed as described in the methods. The final volume did not include the anti-Fab Nb during Local Refinement due to relatively poor densities. **(a)** The raw image after motion correction. **(b)** Representative 2D-Classes generated by CryoSPARC program. MelB in nanodiscs. Nb725_4, NabFab, and anti-Fab Nb can be easily recognized. **(c)** GSFSC resolution was calculated by cryoSPARC Validation (FSC) using two half maps generated by the CryoSPARC Local Refinement program. The number of particles used for the volume reconstruction was presented. **(d)** Particle distribution of orientations over azimuth and elevation angles generated by CryoSPARC Local Refinement program. **(e&f)** The structure of $MelB_{St}$/Nb725_4/NaFab complex. The volume (*e*) and cartoon representation (*f*) were colored by polypeptide chains as indicated. Nanodiscs were transparent and colored in light gray. Sphere and sticks in the panel *f* highlighted Na^+ and its ligands.

presence of $EIIA^{Glc}$ or binds to $EIIA^{Glc}$ in the absence or presence of either of the three Nbs. The data lead to this conclusion that the Nb and $EIIA^{Glc}$ recognize two spatially distinct epitopes of $MelB_{St}$, so it is highly like that the inward-open conformation mimics the conformation of $MelB_{St}$ under the $EIIA^{Glc}$ regulation.

$MelB_{St}$ trapped in a Na^+-bound, low sugar-affinity state

Between helices-II&IV, one Na^+ cation was modeled, liganded by four side-chains, Asp55, Asn58, Asp59 (helix-II), and Thr121 (helix-IV), at distances of between 2.1-2.8 Å (**Fig. 3a**). The backbone carbonyl oxygen of Asp55 is also in close proximity to the bound Na^+. The local resolution of this binding pocket is approximately 2.9-3.2 Å. The model to map *Q*-scores for Na^+ and the binding residues and side-chains are generally greater than the expected scores at this resolution except for the Thr121 side-chain, which has a lower score[42]. The observation of this cation-binding pocket is supported by previous extensive data[17,43,44]. Cys replacement at position Asp59 changes the symporter to a uniporter[19]. The D59C mutant does not bind to Na^+ or Li^+ as well as loses all three modes of cation-coupled transport but catalyzes melibiose fermentation in cells (melibiose concentration-driven transport)[19] or melibiose exchange in membrane vesicles[11]. Asp55 also plays a critical role in the binding of Na^+ or Li^+ and in coupled transport[11,17]. Extensive studies of *E. coli* MelB also show that both negatively charged residues are involved in cation binding[21,45,46]. Thr121 has been determined to be critical for Na^+, not H^+ nor Li^+[44]; and the Cys mutation at Asn58 also loses Na^+ binding[11]. Interestingly, the Na^+ recognition can be selectively eliminated by specific mutations. Further, the Na^+ binding is supported by MD simulations at both inward and outward states using MD simulations in the absence of the Nb **(sFig. 9a-c)**, which reveals the ideal coordination geometry for Na^+ binding.

The crystal structure of D59C $MelB_{St}$ [PDB ID 7L17], with an intact sugar-binding and translocation pathway, show that the sugar-binding pocket is formed by both N- and C-terminal bundles[19]. Eight N-terminal residues (Lys18, Asp19, Ile22, Tyr26, Tyr120, Asp124, Trp128, and Arg149), especially the four charged residues, form the multiple polar interactions with one surface of the galactopyranosyl moiety. Five C-terminal residues (Trp342, Gln372, Thr373, Val376, and Lys377) form a non-specific barrier without a strong polar interaction **(Fig. 3b)**. Due to the D59 mutation, the cation-binding pocket is loosely packed and Asp55 forms a salt-bridge interaction with Lys377 in this uniport mutant, but it is in close proximity to the sugar-specificity determinant pocket as shown in the surface representation. When overlaying the inward-facing structure upon the outward-facing structures, little variation of the positioning of the N-terminal sugar-binding residues is observed except for Arg149, but all C-terminal residues show greater displacements **(Fig. 3c, sticks in black)**. In the inward-facing structure, Lys377 is closer to Asp124, and Asp55 is liganded with Na^+.

The loosely arranged sugar-binding residues observed in the Nb725_4-bound conformation provide the structural foundation for measured lower sugar affinities (**Table 2**), so this structure represents an intracellular Na^+-bound sugar-releasing conformation. Since the positioning of the key residues for galactoside specificity (Lys18, Asp19, and Asp124) exhibits virtually no change, it is conceivable that this conformation retains the initial recognition of sugar for reversal reactions, a common feature for carrier transporters[25,47].

Conformational changes between inward- and outward-facing states

The outward-facing structure [PDB ID 7L17] was trimmed to match the residues resolved in the inward structure [PDB ID 8T60]. The superposition of the outward- and inward-facing $MelB_{St}$ exhibited rmsd of all atoms of 5.035 Å **(sFig. 10a)**, and the major displacement exists at both ends of transmembrane helices. The alignment based on the N-terminal positions 2-200 or the C-terminal positions 231-432 exhibits a clear difference in the angle of the domain packing (**sFig.**

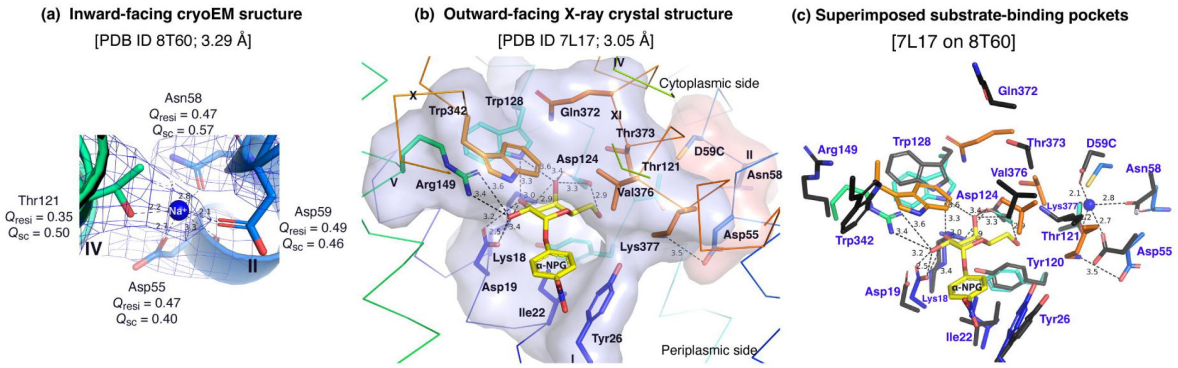

Fig. 3.

Na^+-binding and sugar-binding pockets.

(a) Na^+-binding pocket in the inward-facing conformation (PDB ID 8T60). The isomesh map was created by the Pymol program using level 10 and carve of 1.8. The Na^+ coordinates were shown in dash lines and interacting residues were shown in sticks. Q_{res}, *Q* score for residue; Q_{sc}, *Q* score for side-chain. **(b)** Galactoside-binding pocket in the outward-facing conformation [PDB ID 7L17]. All polar interactions between the bound α-NPG and D59C $MelB_{St}$ were indicated by dash lines and the pocket was also shown in surface representation in blue. The Na^+-binding residues were highlighted by sticks and surface representation in pink. The cytoplasmic and periplasmic sides were labeled. **(c)** Superimposed co-substrate-binding pockets. The a-NPG-bound outward-facing structure [7L17] in *b* was aligned on the inward-facing structure based on the 2-200 region. The residues in the sugar- and cation- binding pockets, as presented in the outward-facing structure in *b*, were colored in black and labeled in blue in the inward-facing structure. a-NPG and Na^+ were colored yellow and blue, respectively.

10b&c). The focused alignment of positions 2-200 or 231-432 exhibits greatly reduced rmsd values (**sFig. 10d&e**). The N-terminal domains at both conformations are virtually the same, especially for the helices-I, -II, and -IV that host the sugar- and cation-specificity determinant pockets (**sFig. 10f**). Some structural rearrangements within 3-5 Å exist in the C-terminal bundle, especially on both ends of cavity-lining helices (VII, VIII, X, and XI) and their link or extended loop (**sFig. 10g&h**). Thus, the conformational changes between the outward- and inward-facing states can be adequately described by a rocker-switch-like movement with some structural rearrangements in the C-terminal bundle as indicated in **sFig.11**.

Substrate translocation barriers

The two structures clearly reveal the two essential barriers critical for substrate translocation, the thicker inner barrier in the outward structure and the thinner outer barrier in the inward structure (**Fig. 4a&c**). The core of the inner barrier is formed by three-helix pairs from both domains (V/VIII, IV/X, and back II/XI), and stabilized by an extensive charged network (**Fig. 4b**)[11,16,19,48]. The N-terminal Arg141 (helix-V) forms salt-bridge interactions with the C-terminal Asp351 and Asp354 (helix-X), and this core interaction links with four other charged residues to stabilize the cytoplasmic closure by forming an inner barrier. In addition, the inner barrier is also stabilized by two peripheral amphiphilic helices at the cytoplasmic side (in the middle loop and the C-terminal tail) (**Fig. 4b**). The entire middle $loop_{6\text{-}7}$ across the two domains interact with broader areas (the N-terminal $loop_{2\text{-}3}$, $loop_{4\text{-}5}$, and helices-II & -IV, as well as the C-terminal $loop_{10\text{-}11}$, helices-X & - XI, and the C-terminal tail). The C-terminal tail helix interacts with both N- and C-terminal domains (helices-V & -X). The contacting area between the two bundles (based on positions 2-212 and 213-450) is 2218 $Å^2$ with nine salt-bridge and five hydrogen-bounding interactions.

The core of the outer barrier in the inward-facing structure also is also formed by three-helical pairs from both domains (V/VIII, I/VII, and II/XI) (**Fig. 4f**). The longest $loop_{11\text{-}12}$ at the periplasmic side moves into the middle area and forms contacts with helices-I and -VII, sealing the periplasmic opening. Notably, helical pair I/VII or IV/X is only involved in the outer or inner barrier, respectively, and the other two cavity-lining helical pairs (V/VIII and II/XI) are engaged in both barriers (**Fig. 4 bc&ef**). The contact area between the two bundles at the periplasmic side of 1435 $Å^2$ is much smaller. These structural features further supported that the outward-facing state is more stable than the inward-facing $MelB_{St}$. In the inward-facing conformation, all of the salt-bridge interactions are broken (**Fig. 4b&e**), and the Arg141 and Lys138 engage in the binding of Nb725_4 (**sFig. 8c**). Therefore, this cytoplasmic-side charged network is the inner barrier-specific.

Assessed by the sugar-bound structure (**Fig. 4a**), the substrate-binding pocket is outlined by Trp128 and Trp 342 on the inner barrier and Tyr26 on the outer barrier (**Fig. 3b; sFig. 10f**), part of both barriers. Notably, the major binding residues that involve the multiple hydrogen-bonding interactions with the galactosyl moiety are only part of the inner barrier. In the inward-facing state, the inner barrier is broken, which exposes the binding site to the cytoplasm and also results in the interruption of the sugar-binding pocket (**Fig. 4c**). The C-terminal binding residues moved away due to the displacement of the backbone of helices-X/XI, and the sugar-binding residues become loosely organized with a low sugar-binding affinity. The structural features indicated that the molecular mechanisms for the sugar translocation simply result from the barrier switch generating a low sugar-affinity inward state of MelB. The outer barrier does not contain residues essential for galactoside binding, so the break of the outer barrier has a much less profound effect on the sugar-binding affinity.

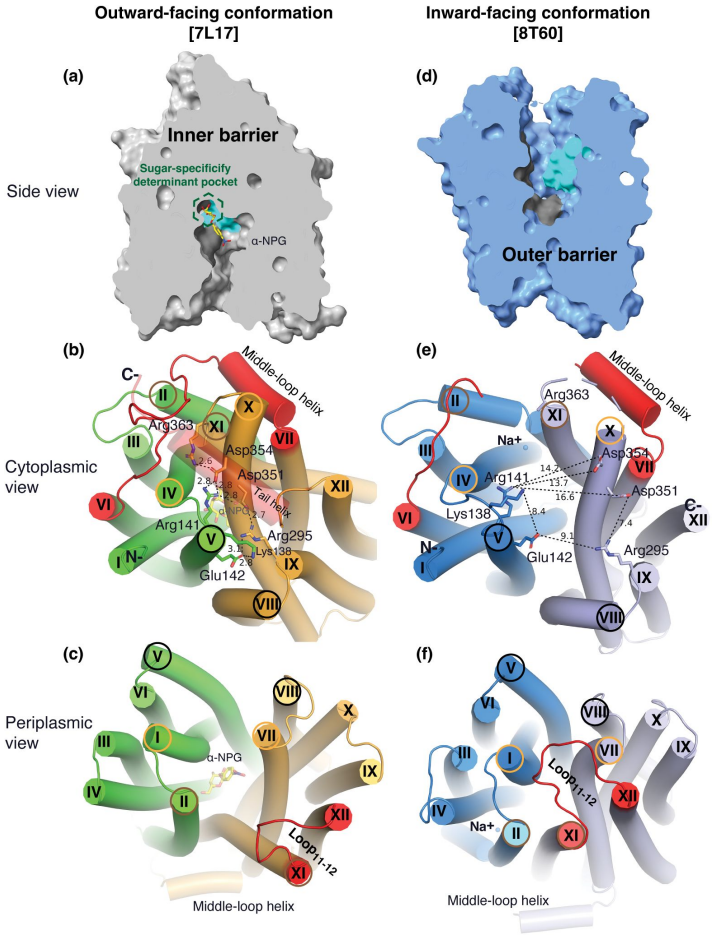

Fig. 4.

Barriers and sugar-binding pocket.

Outward-facing [PDB ID 7L17; left column] and inward-facing [PDB ID 8T60; right column] structures were used to prepare the figures. **(a&d)** Side view with cytoplasmic side on top. The inner and outer barriers were labeled. The sugar-specificity determinant pocket was highlighted in a dashed hexagon. The residues contributing to the bound a-NPG (colored yellow) in N- and C-terminal bundles were colored dark gray and cyan, respectively. **(b&e)** Cytoplasmic view. The charged network between the N- and C-bundles were colored in green and bright orange in panel *b*, or blue and light blue in panel *e*, respectively. The middle loop and the C-terminal tail were colored in red and the C-terminal helix panel *b* was set in transparent and missed in the inward-facing conformation. The charged residues were highlighted in sticks. Arg363 missed the sidechain in the inward-facing structure. **(c&f)** Periplasmic view. $Loop_{11\text{-}12}$ was colored in red. The labels of the paired helices involved in the formation of either barrier were cycles in the same colors. The a-NPG was colored in yellow (*b*&*c*) and Na^+ was shown in blue sphere (***e&f***).

Conformational dynamics measured by HDX-MS

Bottom-up HDX-MS measures the exchange rate of amide hydrogens with deuterium by determination of time-dependent peptide level mass spectra[37]. It is a label-free quantitative technique that can disclose the dynamics of a full-length protein simultaneously. This approach was utilized to determine $MelB_{St}$ dynamics in this study. The Na^+-bound WT $MelB_{St}$ proteins exist in multiple conformations including at least the outward- and inward-facing states but strongly favor the outward-facing states. The Nb725_4-trapped $MelB_{St}$ exists only in an inward-facing conformation. A pair of WT $MelB_{St}$ and WT $MelB_{St}$ complexed with Nb725_4 was subjected to in-solution HDX-MS experiments. $MelB_{St}$ yields 86% coverage with 153 overlapping peptides at an average peptide length of 9.3 residues **(Fig. 5a, sFig. 12; sTable 2**), leaving 66 non-covered residues; most are located in the middle regions of transmembrane helices or in a few cytoplasmic loops (**Fig. 5b, ball in gray)**.

The effect of $MelB_{St}$ structural dynamics imposed by Nb725_4 is presented as the differential deuterium labeling (ΔD). As shown in the residual plot of each peptide between the two states ($D_{Nb725_4\text{-bound} - Nb\text{-free}}$) **(Fig. 5a)** at three labeling time points, variable levels of protections (less deuterium exchange in the complex state) are observed in $MelB_{St}$. A slight deprotection is only observed at the N-terminus. After proper statistical analysis, there are 232 positions (>50% labeled positions) exhibiting insignificant HDX changes ($D_{Nb725_4\text{-bound} - Nb\text{-free}}$ value < |0.3184| or P > 0.05) as indicated by ribbon representation **(Fig. 5a)**. The remaining 177 positions covered by 71 overlapping peptides show statistically significant changes ($D_{Nb725_4\text{-bound} - Nb\text{-free}}$ value ≥ |0.3184| and P ≤ 0.05) and are highlighted by cartoon representation (**Fig. 5b**). The deuterium uptake curves covering 3-magnitude time points were plotted for representative peptides **(Fig. 5b, insets)**. Most Nb725_4 binding residues are not covered except for Lys138 and Arg141 on a corner of the binding stretch. Depending upon the exchange rate and response to the binding of Nb725_4, the $MelB_{St}$ HDX can be categorized into four groups.

Group-I peptides show low-level HDX exchange rates and Nb725_4 afforded complete inhibition for up to at least 50 min (**Fig. 5b, blue**). These peptides are located in transmembrane helices, middle-loop helix, and C-terminal periplasmic loops across both domains and most are clustered at the cavity-lining helices. Group II peptides show faster deuterium uptake over time (**Fig. 5b, deep olive**). The Nb725_4 binding affords small to moderate protections. The group-II peptides are spotted at three cytoplasmic regions; interestingly, all surround the helix-X, which plays a critical role in the stability of the inner barrier. At the inward-facing structure, most of those residues are either missing or poorly resolved. The deuterium uptakes in the Nb725_4-bound $MelB_{St}$ complex likely result from structural flexibility.

Group-III peptides show higher-level HDX exchange rates of greater than 60% for both bound and free states even at 30 sec (**Fig. 5b, yellow drawing**). Nb725_4 only affords short-time, weak protections. They are located in the C-terminal tail unstructured region, and most of them are structurally unresolved due to severe disorders. Group-VI peptide only contains the short N-terminal tail showing a medium-level uptake (40-50%) across all labeling times, and Nb725_4 affords a slight deprotection due to allosteric changes upon the Nb725_4 binding (**Fig. 5b, red**). The results show that Group III and IV peptides covering both tails are solvent-accessible dynamic regions, which is consistent with the notion that they play little role in transport-critical conformational transitions.

The HDX data of the first two groups were further analyzed. Among the five group-I and four group-II members with faster exchanges as judged by the shortest reaction time of 30 sec **(sFig. 11b)**, except for the two periplasmic $loop_{7\text{-}8}$ (peptide 261-271) and $loop_{9\text{-}10}$ (peptide 317-326), others are clustered on the cytoplasmic side. In the outward-facing structure (**Fig. 6a**), the spotted peptides pack against one another: helix-V (peptide 137-150) with helix-VIII (peptide 284-289), and the middle-loop helix (peptide 220-233) with helix-X (peptide 364-368). All surround the conformation-dependent charged network. Notably, this short peptide 137-150 links the sugar-

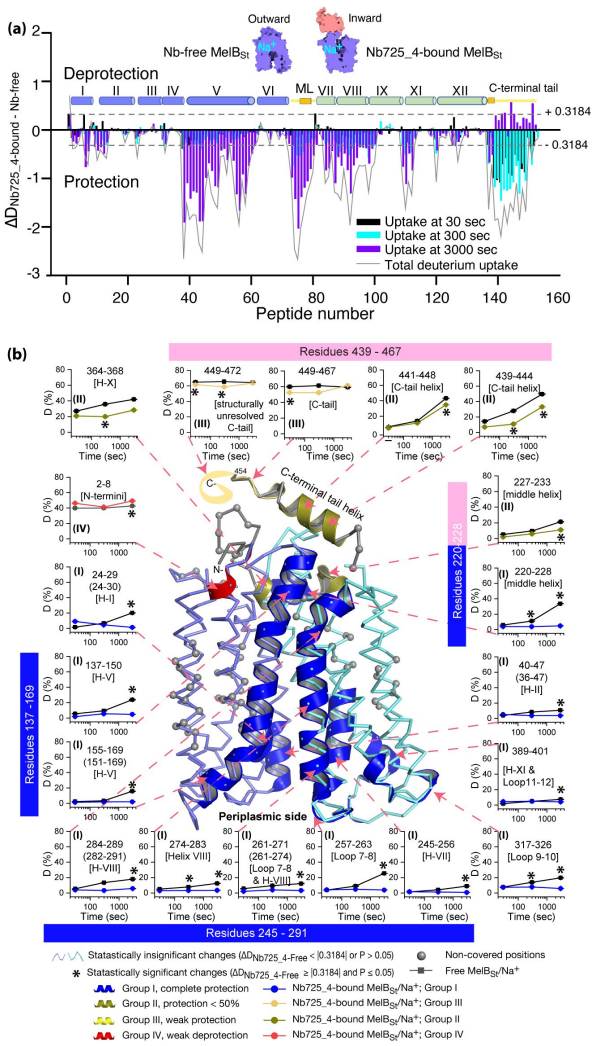

Fig. 5.

$MelB_{St}$ dynamics probed by HDX-MS.

$MelB_{St}$ alone or complexed with Nb725_4 at a 1:2 ratio was 10-fold diluted into the labeling buffer in (25 mM Tris-HCl, pD 7.5, 150 mM NaCl, 10% glycerol, 0.01% DDM in D_2O) and incubated at 20 °C for 30, 300, and 3000 sec, quenched with urea and citric acid pH 2.3. The lipids and detergent were removed by a filter system containing ZrO_2 before performing LC/MS bottom-up HDX as described in Methods. Each sample was analyzed in triplicates. **(a)** Residual plots ($D_{Nb725_4\text{-bound - Nb-free}}$) against peptides for each time point and the sum of uptake. Black, cyan, and blue bars, the deuterium uptake at 30, 300, 3000 sec, respectively; the gray line, the sum of uptake from all three time points. Deprotection, ΔD ($D_{Nb725_4\text{-bound – Nb-free}}$) > 0; deprotection, ΔD < 0. Cylinders, helix positions at the N- and C-terminal domains, as well as loops. Yellow lines, cytoplasmic middle, and C-terminal tail loops. ML, middle loop. **(b)** Mapping of the significant changes at 3000 sec time point on the outward-facing structure [7L17]. Any peptide of ΔD with P ≤ 0.05 and ΔD ≥ |0.3184| were treated as significant and positions were labeled in each time course plot. The representative peptides were also presented by uptake time courses using the percentage of deuterium uptake (D %) relative to the theoretic maximum number (the amino acid residue number minus two ending positions). The residue positions were labeled and the corresponding secondary structure was presented in the square bracket. The positions highlighted in the model were indicated in the uptake plots, either by a single peptide position or by a group of overlapping peptides as shown in the bracket. Error bar, sem; test number, 3. Other symbols were included in the figure.

binding residue Arg149 to the charged network by residues Lys138, Arg141, and Glu142 (**Fig. 4a**). In the inward-facing structure (**Fig. 6b**), these packed helices were moved against one another. Therefore, these higher dynamic regions may play important roles in responding to the ligand binding and initiating the global conformational transition.

Discussion

Formation and stabilization of a high-energy inward-facing conformation of $MelB_{St}$ in a form suitable for structure determination by cryoEM-SPA was a technically-challenging sample preparation problem, which we solved by the formation of a complex of $MelB_{St}$ with a conformation-selective binder and fiducial NabFab. The resulting structure, a high-energy inward-facing, low sugar-affinity state of $MelB_{St}$ with a bound Na^+, represents the intracellular sugar-releasing/rebinding state in the stepped-binding model for the mechanism of coupled transport[15,19] (**Fig. 7**). Our previous results on the cooperativity of binding[28] supported the contention that Na^+ binding increases the melibiose affinity to allow melibiose uptake at lower available concentrations, a critical evolved mechanism for cation-coupled transporters. The new Na^+-bound sugar-releasing inward-facing cryoEM structure provides a structural basis to support the model based on a sequential process in which the sugar binds first and releases second (**Fig. 7**).

The alternating-access movement has been widely used to describe the conformational change of transporters[3,6,7,12,13,26,27]. This description focuses on how the substrates access their binding site or leave the protein. The core symport mechanism for coupled substrate translocations is the mobile barrier involving the inner and outer barriers as proposed originally by Peter Mitchell[49] (**Fig. 4a&d**). Our binding thermodynamic cycle study on the determination of heat capacity change (ΔC_p) showed positive values with the binding of one substrate (suggesting the dominance of hydrations and opening of the transporter), and negative values with the second substrate binding (suggesting dehydration and transition to the occluded intermediate state at step-3) (**Fig. 7**)[28]. The data fit well with a barrier mechanism that both prevents a single substrate molecule from crossing the protein and favors obligatory co-translocation. When this inner barrier breaks as a result of the conformational switch induced by the binding of two substrates, the sugar-binding specific pocket which is part of this inner barrier also breaks (**Fig. 4e**), creating the intracellular sugar low-affinity state and the sugar-releasing path. Collectively, based on structural and thermodynamical analyses, all show that cooperative binding is integral to barrier switching in the core symport mechanism.

For substrate translocation, historically, a two-binding-site model was proposed: a high-affinity site at the outer surface and a low-affinity site at the inner surface. In this functional and structural paradigm, a substrate molecule moves across the protein from its high-affinity binding site to a low-affinity site for subsequent release. This canonical model has been challenged in LacY as the same binding affinity was measured at both the inner and outer surfaces[50], and a single substrate-binding site was also observed in its 3D structures[3,6,26]. Therefore, a single-binding site in the middle of the protein has been the current canonical model. As described, there are two binding affinities detected, dependent upon the co-transported cation, in MelB[17]. One of the major challenges in measuring the substrate binding in membrane transporters is the intrinsic dynamic feature of the transport proteins, which makes it difficult to attribute the outcome to a specific state.

As substrate binding affinity measured in a bulk sample is an average of binding affinities from all of the individual molecules in a distribution, it is challenging to establish a correlation between measured binding affinities and experimentally-determined structures. We approached this problem by using the conformation-specific binding protein Nb725_4 to decouple the binding and conformational dynamics shifting conformers to a single state or a narrowed cluster, i.e., through

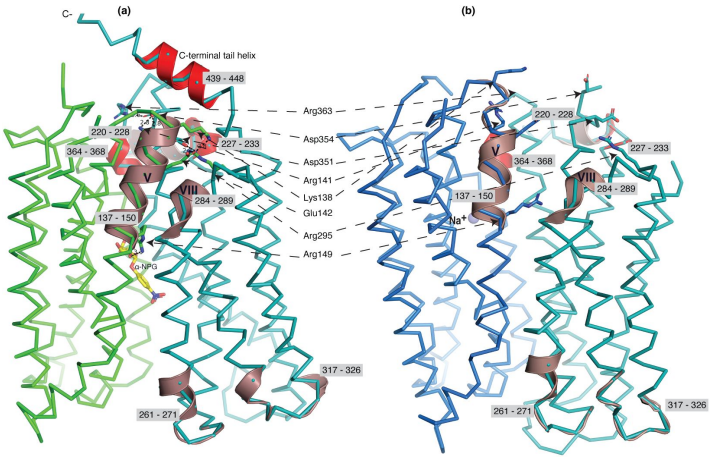

Fig. 6.

Deuterium uptake of $MelB_{St}$.

The peptides that exhibited faster HDX rates (> 5% at 30 sec) were mapped on both the a-NPG-bound outward-facing structure [7L17] in panel ***a*** and the inward-facing Nb725_4-bound structure [8T60] in the panel ***b***, respectively. The peptide positions rwere labeled and the charged residues forming the inner barrier-specific salt-bridge network were indicated. In the Nb725_4-bound structure (*b*), the C-terminal tail was missing. The cartoon colored in dirtyviolet, the group I peptides with faster HDX rate; the cartoon colored in red, group II peptides.

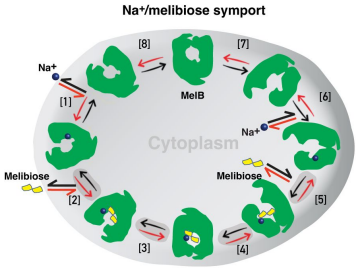

Fig. 7.

Stepped-binding model to explain the Na^+/melibiose symport catalyzed by MelB.

Melibiose active transport begins at step 1 and proceeds via the red arrows around the circle, with one melibiose and one cation inwardly across the membrane per circle. Melibiose efflux transport begins at step 6 and proceeds via the black arrows around the circle, with one melibiose and one cation outwardly across the membrane per circle. Melibiose exchange begins at step 6, and also takes 4 steps involving steps 5 - 2 as highlighted in green color.

experimental modulation of the distribution. The complementary results of the structure and binding affinities permitted the extension of the current single substrate-binding site (and single affinity) model to a more refined model of one site possessing conformation-dependent higher-affinity and lower-affinity states. Identification of the critical inward-open lower-affinity state of the sugar-binding site is significant for understanding the molecular basis of higher intracellular substrate accumulation.

The shared cation site for Na^+, Li^+, or H^+, which is hosted only by the N-terminal two helices (II and IV), is in close proximity but not part of the mobile barrier at either outward- and inward-facing state. Consistently, the simulated Na^+-binding site at both conformations is virtually identical (**sFig. 9**), which is in stark contrast to the conformation-dependent sugar binding in $MelB_{St}$, and this observation could suggest a mechanism for ensuring the reversible reaction by adapting to the *E. coli* intracellular Na^+ homeostasis maintained to 3-5 mM[51]. The measured Na^+ binding affinity to the Nb-trapped $MelB_{St}$ is slightly better than the apo state[17], which may be modulated by the Nb binding.

To interrogate the structural dynamics of $MelB_{St}$ and conformational switch mechanisms, an HDX-MS comparability study in the absence or presence of the conformational Nb725_4 was performed. This powerful approach for characterizing protein conformational flexibility[37,38] has recently been applied to membrane transport proteins[52–54]. Under experimental conditions, two major parameters (solvent accessibility and hydrogen protonation) contribute to the H/D exchange rate. The residual plot clearly indicates that the major effects of Nb725_4 binding are to restrain the conformational dynamics of $MelB_{St}$ (**Fig. 5a**). Stronger protections are observed at both transmembrane helix bundles, especially both ends of the cavity-lining helices (**Fig. 5b, blue**), which marks the most conformationally dynamic regions that correlate to the conformational transition in $MelB_{St}$. Notably, the Nb-free Na^+-bound WT $MelB_{St}$ exists in both outward- and inward-facing conformations with a bias towards the outward[11,19], and the $MelB_{St}$ in the Nb725_4 complex exists only as an inward-facing conformational ensemble. Therefore, differences observed by HDX-MS between the two samples in the absence and presence of Nb725_4 likely encode both $MelB_{St}$ conformational motions and conformational transitions.

While the resolution of HDX is at a peptide level, the data showed marked effects on two well-conserved cytoplasmic helices of MFS transporters (the middle loop and C-terminal tail). Those peripheral amphiphilic helices are likely to play important roles in the stability of the inner barrier necessary. Consistently, a recent atomic force microscopy study has shown that the middle loop becomes loosely packed in the presence of both sugar and cation[20].

As described, the peptide 137-150 of helix-V contains a sugar-binding residue Arg149 and three conformation-critical residues Lys138, Arg141, and Glu142 in the inner barrier-specific charged network (**Fig. 4**). Extensive site-directed mutagenesis and second-site suppression showed that this charged network play important role in the conformational changes and the mutations at all three Arg at positions 141, 295 and 363 (**Fig. 4b**) can be substantially rescued by a single mutation D35E (helix-I) located at the other side of the membrane[48]. Arg141 and Glu142 of *E. coli* MelB have been shown to participate in the conformational transition[55]. Pro148 has been identified by second-site mutation to reduce the transport V_{max} of a V_{max} elevated mutant by modulating the rate of conformational change[56]. Thus, the helix-V dynamic region (peptide 137-150) could link the sugar-binding pocket with the inner barrier-specific salt-bridge network. Together with the interactions with the dynamic regions (residues 284-289) of helix-VIII, the substrate binding occupancy could be propagated, via an allosteric mechanism, from the sugar-binding pocket to the cytoplasmic peripheral helices as a pre-transition for the opening of the transporter to the cytoplasm.

All of the conformation-selective nanobodies (Nb725, Nb733, and the hybrid Nb725_4) are expected to bind $MelB_{St}$ similarly and trap it at the high-energy state, which is consistent with the observation of very low-frequency occurrence during Nbs selection[29]. Extensive analyses and comparisons with the regulatory protein $EIIA^{Glc}$ binding to $MelB_{St}$ revealed that these Nbs binding mimics the regulatory effect imposed by $EIIA^{Glc}$ binding[33,34]. Further, the Nbs and $EIIA^{Glc}$ can concurrently interact with $MelB_{St}$, so there are two spatially discrete binding sites for the two types of binders at the inward-facing conformation. Therefore, the inward-facing structure determined by cryoEM-SPA mimics the regulatory state of MelB during the catabolite repression mechanism, a mechanism that allows the bacteria to selectively utilize favored glucose among a mixture of different carbon sources[30–32].

In this study, we demonstrated that the mobile barrier mechanism plays a central role in substate translocation, the barrier dynamics are modulated by the cooperative binding of substrates, and the inner/outer barrier shifting directly regulates the sugar-binding affinity, with no effect on the cation-binding site. Further, we also proposed that the functional inhibition of this MFS transporter by the central regulatory protein $EIIA^{Glc}$ is achieved by trapping $MelB_{St}$ in a low-sugar affinity inward-facing state. Overall, our studies provide substantial information to explain the obligatorily coupled transport of Na^+ and sugar substrate in structural and dynamic terms collectively.

Methods

Reagents

MacConkey agar media (lactose-free) was purchased from *Difco.* Unlabeled melibiose and 4-nitrophenyl-α-D-galactopyranoside (α-NPG) were purchased from Sigma-Aldrich. Maltose was purchased from *Acros Organics* (*Fisher Scientific*). [1-^{3}H]Melibiose (5.32 Ci/mmol) was custom synthesized by *PerkinElmer*. Detergents undecyl-β-D-maltopyranoside (UDM) and n-dodecyl-β-D-maltopyranoside (DDM) were purchased from *Anatrace*. *E. coli* lipids (Extract Polar, 100600) were purchased from *Avanti Polar Lipids, Inc*. Oligodeoxynucleotides were synthesized by *Integrated DNA Technologies*. LC-MS grade water, LC-MS 0.1% formic, LC-MS grade acetonitrile with 0.1% formic acid in water were purchased from Fisher Scientific (Hampton, NH). Guanidine hydrochloride, citric acid, and Zirconium (IV) oxide 5-μm powder were purchased from *Sigma-Aldrich* (St. Louis, MO). Deuterium oxide (99$^+$% D) was purchased from Cambridge Isotope Laboratories (Tewksbury, MA). All other materials were reagent grade and obtained from commercial sources.

Strains, plasmids, and primers

The genotype and source of *E. coli* strains used in this study are described in Supplementary **sTable 3** unless otherwise described specifically. The commercial *E. coli Stellar^{TM} or XL1 Blue* were used for plasmid construction. The *E. coli* DB 3.1 strain was used to construct the *ccdB*-containing universal FX Cloning vectors[57]. *E. coli* DW2 *(melB$^-$lacY$^-$)*[58] was used for functional studies, and DH5*α cyaA$^-$* strain was used for *in vivo* protein-protein interaction assay[29]. *E. coli* BL21 (DE3) strain and *E. coli* ArcticExpress (DE3) strain were used for overexpression nanobodies; *E. coli* BL21 (DE3) C43 strain[59] was used for overexpression NabFab; *E. coli* BL21(DE3) T7 express strain was used to express $EIIA^{Glc}$[33]. The plasmids used or created and primers in this study were also listed in **sTable 3**.

CDR grafting

CDR grafting technique[39] to transfer the binding specificity of $MelB_{St}$ Nbs to the TC-Nb4, which can be recognized by the NabFab, was performed[36] (**sFig. 1a**). The DNA fragment, which carried the hybrid Nb725_4 along with N-terminal pelB signal peptide (MKYLLPTAAAGLLLLAAQPAMA)

and C-terminal HRV-3C protease site (LEVLFQGP) and 8xHis-tag, was synthesized, digested using restriction enzymes NdeI and XhaI, and ligated with the corresponding sites on expression plasmid pET26b+, resulting in the pET26/Nb725_4.

$MelB_{St}$ protein expression and purification

A 10-L fermenter was used for the constitutive expression of $MelB_{St}$ encoded by the expression plasmid pK95ΔAH/$MelB_{St}$/$CHis_{10}$ in the *E. coli* DW2 cells using Luria-Bertani (LB) broth supplemented with 50 mM KPi, pH 7.0, 45 mM $(NH_4)SO_4$, 0.5% glycerol, and 100 mg/L ampicillin. The cultures were grown at 30 °C until A_{280} ~5. The procedures for membrane preparation, extraction with 1.5% UDM or 2% DDM, and cobalt-affinity purifications were performed as previously described[11,17,29]. The eluted $MelB_{St}$ proteins were dialyzed overnight against a buffer of 20 mM Tris-HCl, pH 7.5, 100 mM NaCl, 10% glycerol, and 0.35% UDM or 0.01% DDM, and concentrated with Vivaspin 50 kDa MWCO membrane to approximately 50 mg/mL, stored at −80 °C after flash-frozen with liquid nitrogen.

Overexpression and purification of membrane scaffold protein 1E3D1 (MSP1E3D1)

An expression plasmid pMSP1E3D1 (*Addgene;* plasmid 20066) was used for the overexpression of the MSP1D1E3 with a 7-His-tag and a TEV protease site in the *E. coli* BL21 (DE3)[60,61]. The culture was grown in LB media containing 0.5% glucose at 37 °C, induced by adding 1 mM IPTG at A_{600} of about 0.6, and incubated for another 2.5 hrs. The MSP proteins from the cell lysate were purified with INDIGO Ni-Agarose (Cube biotech) using a protocol as described[28,62]. The eluted proteins were dialyzed against 20 mM Tris-HCl, pH 7.5, and 100 mM NaCl and concentrated to ~ 8 mg/ ml. The His-tag of MSP1E3D1 was removed by a His-tagged TEV protease (at 1:20 mole/mole ratio of TEV:MSP1E3D1) in the same buffer. The His-tagged TEV protease, un-processed His-tagged MSP1E3D1, and free His tag fragments were trapped within the Ni-Agarose column. The processed MSP1E3D1 proteins without a His tag in the flow-through were concentrated to about 6-8 mg/ ml, and stored at −80 °C after flash-frozen with liquid nitrogen.

TEV protease expression and purification

The tobacco etch virus (TEV) encoded by the plasmid pRK792[63] was overexpressed in a tRNA-supplemented BL21-CodonPlus (DE3)-RIPL strain. The cells were grown in LB broth containing 100 µg/mL ampicillin and 30 µg/mL chloramphenicol at 30 °C until A_{600} of 0.8 ~1.0. At this point, the temperature was decreased to 18 °C, and protein expression was induced by 0.5 mM IPTG overnight. The cells in 50 mM KPi, pH 8.0, 500 mM NaCl, and 10% glycerol were lysed by a microfluidizer and the supernatants after removing the cell debris were subjected to affinity chromatography using Talon resin. The eluted proteins were concentrated to ~3 mg/mL and quickly dialyzed against 20 mM Tris-HCl, pH 7.5, 200 mM NaCl, and 10% glycerol for 3 - 4 hours, and stored at −80 °C after flash-frozen with liquid nitrogen. A typical yield can reach >30 mg/L.

$MelB_{St}$ reconstitution into lipids nanodiscs

The $MelB_{St}$ reconstitution was performed as described previously[28]. Briefly, 5.6 mg of *E. coli* polar lipids extract at a concentration of 40 mg/mL solubilized in 7.5% DDM was added to 1 mL of 1 mg of $MelB_{St}$ in 20 mM Tris-HCl, pH 7.5, 100 mM NaCl, 10% glycerol, and 0.35% UDM (~1:350 mole/mole), and incubated for 10 min on ice. MSP1E3D1 proteins were then added into the $MelB_{St}$/lipid mixture at a 5:1 mole ratio (MSP1E3D1:$MelB_{St}$), and incubated at room temperature with mild stirring for 30 min before being shifted to 4 °C with mild stirring. The detergents were removed and subsequent $MelB_{St}$ lipids nanodiscs were formed by stepwise additions of Bio-beads SM-2 resin (500 mg and then an additional 300 mg after 2 h) and further incubated overnight. After separating the Bio-beads SM- 2 resins, the $MelB_{St}$ lipids nanodiscs were isolated by absorbing onto Ni-NTA beads and the $MelB_{St}$-free empty nanodiscs were in the void due to His-tag being

removed. The $MelB_{St}$ lipids nanodiscs were eluted by adding 250 mM imidazole and the elutes were dialyzed against 20 mM Tris-HCl, pH 7.5, and 150 mM NaCl, and concentrated to ~ 3-4 mg/mL. After ultracentrifugation at ~352000 g (90,000 rpm using a TLA-120 rotor) in a Beckman OptimaTM MAX Ultracentrifuge for 30 min 4 °C, the supernatant containing $MelB_{St}$ lipids nanodiscs were stored at −80 °C after flash-frozen with liquid nitrogen.

Nbs expression and purification

E. coli BL21(DE3) Arctic express cells were used to produce Nbs. The Nb725_4 and anti-Fab Nb were expressed by the expression plasmid pET26/Nb725_4 and pET26/anti-Fab Nb, respectively, containing the *pelB* leader sequence. Nb725 was expressed by the plasmid p7xC3H/Nb725 as described[29]. Cells were grown in Terrific Broth media supplemented with 0.4% (vol/vol) glycerol at 37 °C. Protein expression was induced by adding 1 mM IPTG at the mid-log phase after decreasing the temperature to 25 °C, and the cultures continued growth for 18 to 20 h. The periplasmic extraction of Nbs using sucrose-mediated osmolysis as described[64], and Nb purification was performed by cobalt-affinity chromatography, which yielded ~5 mg/L with >95% purity. The cytoplasmic expression for the Nb725 also provided a similar yield and purity, and all were stable. The purified Nbs were concentrated to ~5-10 mg/mL, dialyzed against 20 mM Tris-HCl, pH 7.5, and 150 mM NaCl, and frozen in liquid nitrogen and stored at −80 °C.

NabFab expression and purification

The NabFab expressing plasmid pRH2.2/NabFab and the expression protocol were kindly gifted from Dr. Kasper P. Locher[36,65]. Briefly, the NabFab was expressed in *E. coli* C43 (DE3) cells in an autoinduction medium at 25 °C for ~18 h. The cells were resuspended in 20 mM Tris-HCl, pH 7.5, 500 mM NaCl, and 1 mM EDTA, and lysed by a microfluidizer. The lysates were subjected to heat treatment at 65 °C for 30 min, followed by centrifugation at 33175 g (15,000 rpm on the rotor JA18) for 30 min at 4 °C to remove insoluble materials. The supernatants were loaded onto the 5-mL Cytivia Protein L column for affinity purification of NabFab proteins. The eluted NabFab in 0.1 M acetic acid, pH 2.0, was neutralized with 200 mM Tris-HCl, pH 8.5, dialyzed against 20 mM Tris-HCl, pH 7.5, 150 mM NaCl, and concentrated up to 5 mg/mg prior to being frozen in liquid nitrogen and stored at −80 °C. The yield for NabFab protein is about 2-3 mg/L.

$EIIA^{Glc}$ expression and purification

The overexpression of unphosphorylated $EIIA^{Glc}$ was performed in the *E. coli* T7 Express strain (New England Biolabs) as described[33].

A bacterial two-hybrid assay

A bacterial two-hybrid assay based on reconstituting adenylate cyclase activities from the T18/T25 fragments of *Bordetella pertussis* adenylate cyclase toxin as described[66,67] was used to examine *in vivo* interaction of Nb and $MelB_{St}$ in *E. coli* DH5α *cyaA* strain[29]. The competent cells were transformed by two compatible plasmids with different replication origins (pACYC/T25:$MelB_{St}$ and pCS19/Nb725:T18 or pCS19/Nb725-_4:T18)[68] containing two hybrids (pACYC)[69] and plated onto the lactose-free MacConkey agar plate containing 30 mM maltose as the sole carbohydrate source, 100 mg/L ampicillin, 25 mg/L chloramphenicol, and 0.2 mM IPTG, and the plates were incubated in 30 °C for 7 days before photography. Red colonies grown on the MacConkey agar indicated positive fermentation due to the cAMP production derived from the interaction of two hybrids. Yellow colonies denoted no fermentation and no cAMP production.

Sugar fermentation assay

E. coli DW2 cells (Δ*melBΔlacYZ)* were transformed with two compatible plasmids with different replication origins (pACYC/$MelB_{St}$ and pCS19/Nbs)[69] and plated onto the lactose-free MacConkey agar plate containing 30 mM maltose or melibiose as the sole carbohydrate source, 100 mg/L

ampicillin, 25 mg/L chloramphenicol, and 0.2 mM IPTG. The plates were incubated at 37 °C for 18 h before photography. Magenta colonies, a normal sugar fermentation; yellow colonies, no sugar fermentation. The cells carrying two empty plasmids or with $MelB_{St}$ but no Nb were used as the control. Maltose fermentation was another control for the specificity of Nb inhibition.

[^{3}H]Melibiose transport assay and western blot

E. coli DW2 cells (*mel*A$^+$, *melB*$^-$, *lacZ*$^-$*Y*$^-$)[70] were transformed with the two compatible plasmids pACYC/$MelB_{St}$ and pCS19/Nb725 or pCS19/Nb725_4, respectively. The cells transformed with two empty vectors (pACYC and pCS19) or pACYC/$MelB_{St}$ with pCS19 without an Nb were used as the negative or positive control, respectively. The cells were grown in LB broth with 100 mg/L ampicillin and 25 mg/L chloramphenicol in a 37 °C shaker overnight, and inoculated by 5% to fresh LB broth with 0.5% glycerol, 100 mg/L ampicillin, 25 mg/L chloramphenicol, and 0.2 mM IPTG. The cultures were shaken at 30 °C for 5 h. The transport assay was performed at 20 mM Na^+ and 0.4 mM [^{3}H]melibiose (specific activity of 10 mCi/mmol) in 100 mM KP_i, pH 7.5, 10 mM $MgSO_4$ at A_{420} of 10 (~0.7 mg proteins/mL) as described[25,56]. The transport time courses were carried out at zero, 5 s, 10 s, 30 s, 1 m, 2 m, 5 m, 10 m, and 30 m by dilution and fast filtration. The filters were subjected to radioactivity measurements using a Liquid Scintillation Counter. The $MelB_{St}$ membrane expression was analyzed by Western blot using anti-His tag antibody as described[29].

Isothermal titration calorimetry

All ITC ligand-binding assays were performed with the Nano-ITC device (TA Instruments)[17]. All samples were buffer-matched by simultaneously dialyzed in the same buffer, or diluting the concentrated small molecule ligands to corresponding dialysis buffers as described[17,33]. The titrand ($MelB_{St}$) placed in the ITC Sample Cell was titrated with the specified titrant (placed in the Syringe) by an incremental injection of 1.5 - 2 µL aliquots at an interval of 300 sec at a constant stirring rate of 250 rpm. All samples were degassed by a TA Instruments Degassing Station (model 6326) for 15 min prior to the titration. Heat changes were collected at 25 °C, and data processing was performed with the NanoAnalyze (v. 3.7.5 software) provided with the instrument. The normalized heat changes were subtracted from the heat of dilution elicited by the last few injections, where no further binding occurred, and the corrected heat changes were plotted against the mole ratio of titrant versus titrand. The values for the binding association constant (K_a) were obtained by fitting the data using the one-site independent-binding model included in the NanoAnalyze software (version 3.7.5), and the dissociation constant (K_d) = 1/K_a. In most cases, the binding stoichiometry (N) number was fixed to 1.

Protein concentration assay

The Micro BCA Protein Assay (Pierce Biotechnology, Inc.) was used to determine the protein concentration assay. The A_{280} was used for concentration estimation.

Protein complex preparation for grid vitrification

Proteins NabFab, Nb725_4, anti-Fab Nb were mixed at a mole ratio of 1:1.1:1.15. The final complex was obtained by adding WT $MelB_{St}$ in nanodiscs based on a mole ratio of 1:1.6 of $MelB_{St}$:NabFab complex. The sample was expected to contain 6 µM $MelB_{St}$, 12 µM MPS1E3D1, 9.5 µM NabFab complex in 20 mM Tris-HCl, pH 7.5, 150 mM NaCl (~1.5 mg/mL). The complex was also analyzed by gel-filtration chromatography using GE Superdex 200 column on a BioRad NGC Chromatography System. Peak fractions were examined by SDS-15% PAGE stained by silver nitrate.

Grids vitrification and single-particle cryoEM data acquisition

Grids preparation and data collection were carried out in S^2C^2 (Menlo Park, CA). The WT $MelB_{St}$/Nb725_4/NabFab/anti-NabFab Nb complex was thawed out from −80 °C storage. Aliquots of 3 µL of samples at 0.75 mg/ml or 1.5 mg/ml protein concentration were placed on 300-mesh Cu

holey carbon grids (Quantifoil, R1.2/1.3) after glow-discharge (PELCO easiGlow™) at 15 mA for 30 sec, and blotted on two sides for 3 sec at 4 °C and 100% humidity before vitrified in liquid ethane using a Vitrobot Mark IV (Thermo Fisher). The grids were subsequently transferred to a Titan Krios (G3i) electron microscope (Thermo Fisher) operating at 300 kV and equipped with K3 direct electron detector (Gatan) and BioQuantum energy filter. The best grids were found from the sample at 1.5 mg/ml concentration.

A total of 14,094 and 8715 movies were automatically collected using the EPU Data Acquisition Software (Thermo Fisher) for non-tilted and 30-degree tilted collections, respectively. Both datasets were collected at a 0.86 Å pixel size and a dose of 50 $e^{-}/Å^{-2}$ across 40 frames (0.0535 or 0.07025 sec per frame for the non-tilted and tilted data collection, respectively) at a dose rate of approximately 23.36 or 17.8 $e^{-}/Å^{2}/s$, respectively. A set of defocus values was applied ranging from −0.8, −1.0, −1.2, −1.4, or −1.8 µm with an energy filter slit width of 20 eV and a 100 µm objective aperture.

Single-particle data processing

All cryoEM single-particle data processing was performed using CryoSPARC program (v. 2 – 4.01) (**sFig. 4**). All imported movies were aligned using defaulted Patch Motion Correction and followed with defaulted Patch contrast transfer function (CTF) Estimation. Micrographs were then curated based on CFT Estimation, astigmatism, and ice thickness, which resulted in 13,649 and 7,129 micrographs for the non-tilted and 30-degree tilted datasets, respectively.

Initially, particle picking from the 2000 micrographs was performed using Blob Picker using 120 and 160 Å for the minimal and maximal particle diameters, respectively, in the CryoSPARC program **(sFig. 4a)**. A total of 1,087,124 particles were selected and extracted with a box size of 256 pixels. After 2 runs of 2D Classification, five classes were selected as imputing templates in Template Picker. A total of resultant 9,103,229 particles from 13,649 micrographs were extracted with a box size of 384 pixels bin 92 pixels and subjected to iterative rounds of 2D Classification. The yielded 1,245,734 particles were re-extracted at a box size of 416 pixels. After further sorting using 2D Classification, the highly selected 338,883 particles, which clearly contained nanodisc-surrounding $MelB_{St}$ bound with Nb725_4/NabFab/anti-NabFab Nb, were used for Ab-Initio 3D Reconstruction. One out of 5 Ab-Initio classes contained the expected super-complex from a total of 93,693 particles, which allowed for a 3.80 Å volume to be reconstructed using Non-uniform Refinement. The 93,693 particles were then further sorted using heterogeneous refinement with input volumes created by multiclass Ab-initio to a subset of 41,264 particles, which allowed a 3.49 Å volume to be reconstructed using Non-uniform Refinement with a static mask prepared from one of the volumes. This map was successfully used to build the initial model of all four proteins; however, this map was anisotropic and lacked some orientations in angular space. To improve the map quality, two strategies were applied including reprocessing this dataset and performing tilted data collection. The hand of the 3.49 Å volume was changed and used to generate 50 templates.

Template Pick using the 50 templated was applied to the 13,649 micrographs, which generated 7,632,727 particles **(sFig. 4b)**. After extraction at a box size of 384 pixels bin 92 pixels and iterative rounds of 2D Classification and Heterogeneous Refinement, 370,941 particles were selected and re-extract at a box size of 384 pixels. This 370,941-particle set was combined with the previously identified 41,264-particle set after extraction at a box size of 384 pixels and removed duplicate, the subset of 188,566 particles exhibited slightly improved directional distribution. To further explore the first data collection, the previously rejected 2D classes were analyzed and 214,522 particles were selected based on orientation. After combined and iterative rounds of 2D Classification, Heterogeneous Refinement, and Local Refinement, a subset of the 196,254-particle set supported a 3.39 Å volume to be reconstructed using local refinement, and the directional distribution of the map is further improved.

A tilted data collection on the same microscopy and parameter settings was performed with a 30-degree tilt (**sFig. 4c)**. A total number of 7,129 micrographs were obtained. The 50-templates were used for particle pick, which yielded 2,887,147 particles after curation. The particles were extracted using a box size of 384 bin 96 pixels. After 3-run 2D Classification and followed 3-run Heterogeneous Refinement using the 3.39 Å volumes and the other two Ab-initio volumes, a subset of 544,531 particles were re-extracted using a box size of 384 pixels. After further iterative rounds of 2D Classification, Heterogeneous Refinement, and Local Refinement, 182,101 particles were obtained for the tilted collection, which could support a 4.01 Å volume using Local Refinement and directional distribution focused on the missing angles in the first dataset.

A total number of 378,355 polished particles from both non-tilted and 30-degree tilted data acquisition were used to reconstruct a 3.40 Å volume using Local Refinement, and the 30-degree tilted data filled the missing particle orientations but the resolution was not improved. The particles were subjected to 3D Classifications using a target resolution of 3.3 Å and 10 classes and the highest resolution classes were collected. The final collected 296,925-particle set supported a 3.37 Å volume to be reconstructed using Local Refinement and a static mask covering $MelB_{St}$, Nb725_4, and NabFab. The reporting GSFSC resolution of 3.29 Å was calculated by Validation (FSC) using the two half maps, and the particle distribution was calculated by ThereDFSC (**sFig. 5**).

The initial mask for Non-uniformed Refinement was created in UCSF ChimeraX using the volume generated from Ab-Initio 3D Reconstruction which covered the full complex. The refinement masks for final-stage Local Refinement only covered $MelB_{St}$, Nb725_4, and NabFab and filtered at a low pass to 10 Å and soft padding width of 10. The 3D Classification used the full-covered mask as the solvent mask and the refinement masks in the Local Refinement as the focus mask.

Local Refinement set the initial low pass resolution of 8 Å, use of pose/shift Gaussian prior during alignment, Rotation search extent of 9 °, and Shift search extent of 6 Å. The final 3.29 Å volume was sharpened in Phenex auto_sharpen program[71]default setting for model refinement.

Model building and structure refinement

The initial model building was carried out based on the 3.45 Å reconstruction map obtained from the first dataset. The coordinates of $MelB_{St}$ D59C (PDB ID 7L17), NabFab and anti-NabFab Nb (PDB ID 7PHP), and a sequence-based 3-D model generated by AlphaFold 2 were fitted into the map in UCSF ChimeraX[72]. The N-terminal helices of $MelB_{St}$ fit well and the C-terminal helices were manually fitted into the initial map. The sequence of $MelB_{St}$ D59C was mutated back to wild type in COOT[73]. All 4 chains were changed to poly-Ala peptides and the side chains of each residue were rebuilt. Structure refinement was performed using phenix.real_space_refine application in PHENIX[74] in real space with secondary structure and geometry restraints.

The model was refined against the final map at a resolution of 3.29 Å after sharpening using PHENIX auto_sharpen program default setting[71]. A cation Na^+ was modeled in the density between helices-II and -IV in COOT. After runs of refinement and remodeling, in total, 417 residues of $MelB_{St}$ (positions 2-210, 219-355, and 364-432), with 6 unassigned side-chains at the C-terminal domain (Leu293, Tyr355, Arg363, Tyr369, Tyr396, and Met410) due to the map disorder, 122 residues of Nb725_4 (2-123), 229 residues of NabFab H-chain (1-214), and 210 residues of NabFab L-chain (4-213), were modeled, respectively. There are three $MelB_{St}$ regions with missing densities including the middle loop righter after the Nb binding site (positions 211-218), $loop_{10\text{-}11}$ (356-361), and the C-terminal tail after residue Tyr432. In addition, the densities between positions 219-230 and regions close to the missing densities at $loop_{10\text{-}11}$ are very weak. Statistics of the map reconstruction and model refinement can be found in **sTable 1**. The model-map fitting quality was evaluated by *Q* score program[42]. Pymol[75] and UCSF chimera or ChimeraX[72] were used to prepare the figures.

All-atom molecular dynamics (MD) simulations

All-atom MD simulations were performed taking the inward-facing CryoEM structure as the starting model. Atom coordinates in the loops missing from the CryoEM structure were filled in using homology modeling with the Modeller software package[76]. Subsequently, the protein was embedded into a lipid bilayer composed of 1-palmitoyl-2-oleoyl phosphatidylethanolamine (POPE), 1-palmitoyl-2-oleoyl phosphatidylglycerol (POPG), and cardiolipin (CDL), in a molar ratio of 7:2:1 for POPE:POPG:CDL, mimicking the membrane composition of *E. coli.* Each side of the lipid bilayer was then enclosed by a box of water molecules with 25 Å thickness. Sodium chloride ions were introduced among these water molecules to yield a solution with an approximate concentration of 0.16 M. The system setup was performed via the CHARMMGUI[77] web interface. The all-atom MD simulations for the outward-facing $MelB_{St}$ under the same setup have been reported by constructing through an in-silico mutation, converting the outward-facing crystal structure of the D59C $MelB_{St}$ mutant (PDB ID 7L16) back to the WT MelB [44]. In both the inward and outward-facing configurations, a sodium ion was initially situated in the binding site, while melibiose was notably absent from the system. Each system underwent initial optimization where the heavy atoms of proteins and lipids were harmonically restrained, employing a force constant of 1000 kJ/mol/$Å^2$. This was followed by 100 picoseconds (ps) of dynamics at a temperature of 300 K in the constant NVT ensemble. Subsequently, the restraints were gradually reduced during 10 ns of dynamics in the constant NPT ensemble, maintained at a temperature of 300 K and pressure of 1 atm. For equilibration, we carried out an additional 30 ns of dynamics in the NPT ensemble under the same conditions, but without any restraints. After the equilibration stage, 1 μs of dynamics was performed in the constant NPT ensemble, under the same temperature and pressure, to generate the production trajectories. We maintained the temperature using a Langevin thermostat with a friction coefficient of 1 ps^{-1}. The trajectory was propagated with a timestep of 2 femtoseconds (fs), and all bonds involving a hydrogen atom were constrained. The CHARMM36 force field[78–80] was utilized to simulate the protein, lipid, and ions throughout all simulations. Electrostatic interactions were calculated using the particle mesh Ewald method, with a tolerance of 5 x 10^{-4}. We set the cutoff for van der Waals interactions at 12 Å. The TIP3P model[81] was used to treat water molecules and ions. All classical MD simulations were performed using the OPENMM[82] software package.

Hydrogen-deuterium exchange coupled to mass spectrometry (HDX-MS)

In-solution pairwise HDX-MS experiment was performed to study the structural dynamics of $MelB_{St}$. Labeling, quenching, lipids removal, and online digestion were achieved using a fully automated manner using HDx3 extended parallel system (LEAP Technologies, Morrisville, NC)[83,84].

Working samples of $MelB_{St}$ and $MelB_{St}$ complexed with Nb725_4 were prepared to a concentration of 50.0 μM for $MelB_{St}$ and 100 μM for Nb725_4 in a buffer of 25 mM Tris-HCl, pH 7.5, 150 mM NaCl, 10% glycerol, 0.01% DDM in H_2O. Aliquots of 4 μl of each working sample were diluted by 10-fold into the labeling buffer of 25 mM Tris-HCl, pD 7.5, 150 mM NaCl, 10% glycerol, 0.01% DDM in D_2O. The reactions were incubated in D_2O buffer at 20 °C for multiple time points (30 sec, 300 sec, and 3000 sec) in triplicates and non-deuterated controls were prepared in a similar manner except H_2O buffer was used in the labeling step. The pH of the labeling buffer was measured with a pH meter mounted with a glass electrode and then corrected to pD (pD = pH + 0.4).

The reactions were quenched at given time points by adding the same volume of ice-cold 6 M urea, 100 mM citric acid, pH, 2.3 in water for 180 seconds at 0 °C and immediately subjected to a lipid filtration module containing ZrO_2 available on the LEAP PAL system. After incubation of 60 sec, the LEAP X-Press then compressed the filter assembly to separate proteins from the ZrO2 particles-bound phospholipids and detergents. The filtered protein sample was injected into a cool box for online digestion and separation.

LC/MS bottom-up HDX was performed using a Thermo Scientific™ Ultimate™ 3000 UHPLC system and Thermo Scientific™ Orbitrap Eclipse™ Tribrid™ mass spectrometer. Samples were digested with a Nepenthesin-2 (Affipro, Czech Republic) column at 8 °C for 180 sec and then trapped in a 1.0 mm x 5.0 mm, 5.0 µm trap cartridge for desalting. Peptides were then separated on a Thermo Scientific™ Hypersil Gold™, 50 x1 mm, 1.9 µm, C18 column with a gradient of 10 % to 40 % gradient (A: water, 0.1 % formic acid; B: acetonitrile, 0.1 % formic acid) gradient for 15 minutes at a flow rate of 40 µL/min. To limit carry-over issues, a pepsin wash was added in between runs. To limit the back-exchange of hydrogen, all of the quenching, trapping, and separation steps were performed at near 0 °C.

For data analysis, a nonspecific digested peptide database was created for $MelB_{St}$ with separate tandem mass spectrometry measurements of non-deuterated samples. Digested peptides from undeuterated $MelB_{St}$ protein were identified on the orbitrap mass spectrometer using the same LC gradient as the HDX-MS experiment with a combination of data-dependent and targeted HCD-MS2 acquisition. Using the Thermo BioPharma Finder software (v 5.1), MS2 spectra were matched to the $MelB_{St}$ sequence with fixed modifications. Altogether 153 peptide assignments (confident HDX data cross all labeling times) were confirmed for $MelB_{St}$ samples giving 86% sequence coverage. MS data files were processed using the Sierra Analytics HDExaminer software with the $MelB_{St}$ peptide database. Following the automated HDX-MS analysis, manual curation was performed. Upon the completion of the data review, a single charge state with high-quality spectra for all replicates across all HDX labeling times was chosen to represent HDX for each peptide. Differential HDX data were tested for statistical significance using the hybrid significance testing criteria method with an in-house MATLAB script, where the HDX differences at different protein states were calculated ($\Delta D = D_{Nb725_4\text{-bound}} - D_{Nb\text{-free}}$). D denotes deuteration, defined as the mass increase above the average mass of the undeuterated peptide. Mean HDX differences from the three replicates were assigned as significant according to the hybrid criteria based on the pooled standard deviation and Welch's t-test with $P < 0.01$. The statistically significant differences observed at each residue (ie., $\Delta D \geq 0.3184$ for this study) were used to map HDX consensus effects based on overlapping peptides onto the structure models. Residue-level data analysis was performed using a built-in function in BioPharma Finder software. The parameters included the number of simulations of 200, recorded solutions of 20, Chi2 increase by the larger of smooth absolute of 0, smother relative of 2, differential absolute of 0, and differential relative of 2.

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Competing Interests

Y. S. and R. V. are employees of *Thermo Fisher Scientific*.

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Editors

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Reviewer #1 (Public Review):

Summary: The current study reports a cryo-EM structure of MFS transporter MelB trapped in an inward-facing state by a conformationally selective nanobody. The authors compare this structure to previously-resolved crystal structures of outward-facing MelB. Additionally, the authors report H/D exchange/ mass spec experiments that identify accessible residues in the protein.

Strengths: The authors overcame very significant technical challenges to solve the first inward-facing structure of the small, model MFS transporter MelB by cryo-EM. The use of conformation-trapping nanobodies (which had been reported previously by this group) is particularly nice.

Weaknesses: Maps and coordinates were not provided by the authors, which presents a gap in this assessment.

The authors highlight the use of HDX experiments as a measurement of protein conformational dynamics. However, this experiment does not measure the conformational dynamics of the transporter, since in these experiments exchange is not initiated by ligand addition or another trigger. The experiment instead measures the accessibility of different residues, and of course, a freely-exchanging sodium bound transporter would have more exchangeable positions than when a conformation-trapping nanobody is bound. It is not clear what new mechanistic information this provides, since this property of the nanobody has already been established.

Based on the evidence presented, it is somewhat speculative that the structure represents the EIIa-bound regulatory state.

Reviewer #2 (Public Review):

Summary:
In this manuscript, Hariharan and colleagues present an elegant study regarding the mechanistic basis of sugar transport by the prototypical Na+-coupled transporter MelB. The authors identified a nanobody (Nb 725) that reduces melibiose binding but not Na+ binding. In vitro (ITC) experiments suggest that the conformation targeted by this nanobody is different from the published outward-open structures. They go on to solve the structure of this other conformational by cryo-EM using the Nanobody grafted with a fiducial marker and enhancer and, as predicted, capture a new conformation of MelB, namely the inward-open conformation. Through MD simulations and ITC measurements, they demonstrate that such state has a reduced affinity for sugar but that Na+ binding is mostly unaffected. A detailed observation and comparison between previously published structures in the outward-open conformation and this new conformational intermediate allows to strengthen and develop the mobile barrier hypothesis underpinning sugar transport. The conformational transition to the inward-facing state leads to the formation of a barrier on the extracellular side that directly affects the amino acid arrangement of the sugar binding site, leading to a decreased affinity that drives the direction of transport. In contrast, the Na+ binding remains the same. This structural data is complemented with dynamic insights from HDX-MS experiments conducted in the presence and absence of the Nb. These measurements highlight the overall protective effect of nanobody binding, consistent with the stabilization of one conformational intermediate.

Strengths:
The experimental strategy to isolate this elusive conformational intermediate is smart and well-executed. The biochemical and biophysical data were obtained in a lipid system (nanodiscs), which allows dismissing questions about detergent induced artefacts. The new conformation observed is of great interest and allows to have a better mechanistic understanding of ion-coupled sugar transport. The comparison between the two structures and the mobile barrier mechanism hypothesis is convincingly depicted and tested.

Weaknesses:
This is excellent experimental work. My recommendations stem mostly from concerns regarding the interpretation of the observed results. In particular, I am somewhat puzzled by the important role the authors give to the regulatory protein EIIa with little structural or biophysical data to back up their claims. The hypothesis that the conformation captured by the Nb is physiologically and functionally equivalent to that caused by EIIa binding is definitely a worthy hypothesis, but it is not an experimental result.
Evidence in support could include a structure with EIIa bound. Since it does not bind at the same location as the Nb, it seems feasible. Or, the authors could have performed HDX-MS in the presence of EIIa to determine if the effect is similar to that of Nb_725 binding. In the absence of these experiments, discussion about EIIa should be limited. Along the same lines, I find it misleading to put in the abstract a sentence such as "It is the first structure of a major facilitator superfamily (MFS) transporter with experimentally determined cation binding, and also a structure mimicking the physiological regulatory state of MelB under the global regulator EIIAGlc of the glucose-specific phosphoenolpyruvate:phosphotransferase system." None of this is supported by the experimental work presented in this article: the Na+ is modelled (with great confidence, but still) and whether this structure mimics the physiological state of MelB bound to EIIa is not known. The results of the paper are strong and interesting enough per se, and there is no need to inflate them with hypothesis that belongs to the discussion section.

I also note that the HDX-MS experiments do not distinguish between two conformational states, but rather an ensemble of states vs one state.

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The manuscript authored by Lan Guan and colleagues reveals the structure of the cytosol-facing conformation of the MelB sodium/Li coupled permease using the nab-Fab approach and cryoEM for structure determination. The study reveals the conformational transitions in the melB transport cycle and allows understanding the role of sugar and ion specificities within this transporter.

Strengths: The study employs a very exciting strategy of transferring the CDRS of a conformation specific nano body to the nab-fab system to determine the inward-open structure of MelB. The resolution of the structure is reasonable enough to support the major conclusions of the study. This is overall a well-executed study.

Weaknesses: The authors seem to have mixed up the exothermic and endothermic aspects of ITC binding in their description. Positive heats correspond to endothermic heat changes in ITC and negative heat changes correspond to exothermic heats. The authors seem to suggest the opposite. This is consistently observed throughout the manuscript.

Author Response

> ***Reviewer #1 (Public Review):***
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We appreciate reviewer #1's positive comments.

> *Weaknesses: Maps and coordinates were not provided by the authors, which presents a gap in this assessment.*

We didn't know specific requests for maps & coordinates during the initial submission but will provide them per request.

> *The authors highlight the use of HDX experiments as a measurement of protein conformational dynamics. However, this experiment does not measure the conformational dynamics of the transporter, since in these experiments exchange is not initiated by ligand addition or another trigger. The experiment instead measures the accessibility of different residues, and of course, a freely-exchanging sodium bound transporter would have more exchangeable positions than when a conformation-trapping nanobody is bound. It is not clear what new mechanistic information this provides, since this property of the nanobody has already been established.*

We thank you for your comment. We will address your and reviewer 2's similar questions later.

Based on the evidence presented, it is somewhat speculative that the structure represents the EIIa-bound regulatory state.

We believe that have presented convincing evidence obtained by ITC and gel-filtration chromatography to support this statement. The effects of Nb725 or EIIAGlc on MelB functions are similar: little change in Na+ binding, little change in Nb725 or EIIAGlc binding in the absence or presence of the EIIAGlc or Nb725, but a great reduction in sugar-binding affinity (sFigs. 2&3; tables 1&2; published two papers in J. Biol. Chem. 2014; 289: 33012-33019 and 2023; 299:104967). To make it clear, we will add the related data from the two JBC papers into the table 2. Nb725 and EIIAGlc can concurrently bind to MelBSt (sFigs. 2&3; tables 1&2). Further, we will provide a new figure to show that a complex composed of all three proteins can be isolated by gel-filtration chromatography. We have also established this finding with another Nb733 from the same family (JBC, 2023; 299:104967). However, given the EIIAGlc-bound structure has not been resolved yet, we will tune down the related argument.

Reviewer #2 (Public Review):

Summary: In this manuscript, Hariharan and colleagues present an elegant study regarding the mechanistic basis of sugar transport by the prototypical Na+-coupled transporter MelB. The authors identified a nanobody (Nb 725) that reduces melibiose binding but not Na+ binding. In vitro (ITC) experiments suggest that the conformation targeted by this nanobody is different from the published outward-open structures. They go on to solve the structure of this other conformational by cryo-EM using the Nanobody grafted with a fiducial marker and enhancer and, as predicted, capture a new conformation of MelB, namely the inward-open conformation. Through MD simulations and ITC measurements, they demonstrate that such state has a reduced affinity for sugar but that Na+ binding is mostly unaffected. A detailed observation and comparison between previously published structures in the outward-open conformation and this new conformational intermediate allows to strengthen and develop the mobile barrier hypothesis underpinning sugar transport. The conformational transition to the inward-facing state leads to the formation of a barrier on the extracellular side that directly affects the amino acid arrangement of the sugar binding site, leading to a decreased affinity that drives the direction of transport. In contrast, the Na+ binding remains the same. This structural data is complemented with dynamic insights from HDX-MS experiments conducted in the presence and absence of the Nb. These measurements highlight the overall protective effect of nanobody binding, consistent with the stabilization of one conformational intermediate.

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We appreciate the reviewer's insightful understanding of our novel findings and the associated explanations on the cation-coupled symport mechanisms.

Weaknesses: This is excellent experimental work. My recommendations stem mostly from concerns regarding the interpretation of the observed results. In particular, I am somewhat puzzled by the important role the authors give to the regulatory protein EIIa with little structural or biophysical data to back up their claims. The hypothesis that the conformation captured by the Nb is physiologically and functionally equivalent to that

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As stated in the response to reviewer 1, we believe that we presented strong data to argue for a structure mimicking the physiological regulatory state of MelB. The only missing data is the lack of the structure determination of the EIIA-bound state. We will change the title and tune down the related discussions in a new version.

Regarding our statement in our abstract that “It is the first structure of a major facilitator superfamily (MFS) transporter with experimentally determined cation binding”, we believe that our claim is supported by the resolved Na+ binding in the cryoEM structure. So far, to our knowledge, there was no experimentally determined cation on its canonical binding site reported yet.

> *I also note that the HDX-MS experiments do not distinguish between two conformational states, but rather an ensemble of states vs one state.*

We will address both reviewers 1 and 2 together. We agree with your comments and we compared the one (inward) state and ensembles of (predominantly outward) states. A lot of published data have demonstrated that the WT MelBSt predominantly populates outward-facing states, especially in the presence of Na+. The major differences in HDX-MS between the inward-facing state in the presence of the Nb and the outward-facing ensembles in the absence of the Nb should be related to the conformational changes between the inward- and outward-facing states, but not quantitatively. The type of measurements we performed do not contain information on the rates of conformational changes, but this study identified the dynamics regions involved in this conformational switch.

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This is consistently observed throughout the manuscript.

All of our ITC data are correctly presented. Our data were collected from the NanoITC (TA instruments, Inc), which directly measures the heat release/enthalpic changes and projects exotherm with positive values. This is in contrast to the MicroCal device, which detects heat changes through voltage compensation and exotherm is depicted with negative values. We will further emphasize this in related figure legends.