Multiple conformational switches in a GTPase complex control co-translational protein targeting

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Abstract

The “GTPase switch” paradigm, in which a GTPase switches between an active, GDP-bound state and an inactive, GDP-bound state through the recruitment of nucleotide exchange factors (GEFs) or GTPase activating proteins (GAPs), has been used to interpret the regulatory mechanism of many GTPases. A notable exception to this paradigm is provided by two GTPases in the signal recognition particle (SRP) and the SRP receptor (SR) that control the co-translational targeting of proteins to cellular membranes. Instead of the classical “GTPase switch,” both the SRP and SR undergo a series of discrete conformational rearrangements during their interaction with one another, culminating in their reciprocal GTPase activation. Here, we show that this series of rearrangements during SRP-SR binding and activation provide important control points to drive and regulate protein targeting. Using real-time fluorescence, we showed that the cargo for SRP—ribosomes translating nascent polypeptides with signal sequences—accelerates SRP-SR complex assembly over 100-fold, thereby driving rapid delivery of cargo to the membrane. A series of subsequent rearrangements in the SRP-SR GTPase complex provide important driving forces to unload the cargo during late stages of protein targeting. Further, the cargo delays GTPase activation in the SRP-SR complex by 8–12 fold, creating an important time window that could further improve the efficiency and fidelity of protein targeting. Thus, the SRP and SR GTPases, without recruiting external regulatory factors, constitute a self-sufficient system that provides exquisite spatial and temporal control of a complex cellular process.

Results

General Experimental Approach.

To monitor the different conformational states of the SRP-SR complex, we used fluorescence resonance energy transfer (FRET) between donor and acceptor probes incorporated on both the SRP and SR. FRET provides a highly sensitive assay that allows us to detect the transient early intermediate (Fig. 1; ref. 14). Further, this intermediate can be distinguished from the subsequent conformations because it has a lower FRET value than the closed and activated complexes (Fig. 1; ref. 14). In addition, an environmentally sensitive probe, acrylodan, labeled at residue 235 of the SRP, detects formation of the closed.

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and activated complexes but not the early intermediate (Fig. 1 and Fig. S1), thereby simplifying kinetic and thermodynamic analyses of these later conformations. Finally, acrylodan labeled at residue 356 of the SR near its catalytic loop specifically detects the activated complex (Fig. 1 and Fig. S2). In addition to these fluorescent probes, mutant GTPases and GTP analogues were used to block specific rearrangements and thus isolate each conformational intermediate (10, 11). We can block the early → closed rearrangement by leaving out GTP (Fig. 1; ref. 14); this allows us to isolate the early intermediate and characterize its kinetics and stability. Mutations in the catalytic loop, SRP A144W or SR A335W, allow a stable intermediate (10, 11). We can block the specific rearrangements and thus isolate each conformational intermediate (10, 11). The nonhydrolyzable GTP analogue 5'-guanylylimido-diphosphate (GppNHp) allows most of the rearrangements to occur but inhibits GTP hydrolysis (10, 11). Using these tools, we determined how the SRP and SR GTPases use their probes, mutant GTPases and GTP analogues to block complex (Fig. 1 and Fig. S2). In addition to these fluorescent probes that detect the different conformational stages, as described in the text.

Cargos Accelerates Assembly of a Stable SRP-SR Complex over 100-fold. As cargo, we purified stalled ribosome-nascent chain complexes (RNCs) bearing the N-terminal 74 aa of the model SRP substrate FtsQ (19–21). SRP-SR complex assembly was monitored using FRET in the presence of GppNHp. Comparison of the time courses for complex assembly shows 3 differences between free and cargo-loaded SRP (Fig. 2A): (i) the initial rates are much faster with cargo-loaded SRP; (ii) the kinetics of complex formation with cargo-loaded SRP is bi-phasic with a burst phase, suggesting the accumulation of an intermediate; (iii) at completion of the reaction, FRET plateaus at a lower value for cargo-loaded SRP, suggesting a change in the equilibrium stability of the final SRP-SR complex. These effects are further characterized below.

An observed rate constant for complex formation (k_{obsd}) at any protein concentration is the sum of the complex assembly and disassembly rate constants (Eq. 1; 22)

\[ k_{obsd} = k_{on} \times [SR] + k_{off} \]  

To isolate the effect of cargo on complex assembly, we measured the observed rate constants as a function of SR concentration; the slope of this concentration dependence gives the association rate constant, k_{on} (Eq. 1; Fig. 2B). The value of k_{on} is 4.4 \times 10^4 M^{-1} s^{-1} in the absence of cargo, consistent with previous measurements (10). In the presence of cargo, the complex formation rate constant is 100–400-fold faster (Fig. 2B and SI Text Fig. S3A). Thus, the cargo-loaded SRP has a substantial kinetic advantage over the free SRP to form a complex with the SR, ensuring efficient delivery of cargo to the target membrane.

Cargos Stabilizes the Early Intermediate by Two Orders of Magnitude. The biphasic kinetics with a burst phase during complex formation with cargo-loaded SRP suggests the accumulation of an intermediate (Figs. 2A and 3A, blue). A likely candidate to account for this burst is the early intermediate, which forms quickly and has a lower FRET value than the subsequent complexes (Fig. 1; ref. 14). To test this notion, we blocked the early → closed rearrangement and isolated the early complex by performing complex assembly in the absence of nucleotide (Figs. 1 step 2 and 3A, green). Both the rate and the magnitude of FRET changes for assembly of the early intermediate agree well with those of the burst phase during complex assembly with GppNHp (Fig. 3A). This provides strong evidence that in the presence of cargo, the early intermediate accumulates substantially during complex assembly.

The early intermediate, which lacks stabilizing interactions from the γ-phosphate of GTP, is very unstable without cargo (5, 14), hence it cannot accumulate under the nanomolar concentrations of
SRP and SR used here (Fig. 2A, black). Therefore, it was surprising to detect its accumulation with cargo-loaded SRP. This observation suggests that the cargo strongly stabilizes this intermediate. To test this hypothesis, we determined the equilibrium and kinetic stability of the early complex with and without cargo. Indeed, the cargo stabilizes the early complex over 50-fold, increasing its equilibrium dissociation constant ($K_d$) from 4–10 μM (14) to 80 ± 4 μM (Fig. 3B, squares) and decreasing its dissociation rate constant ($k_{off}$, derived from the y-intercept in Fig. 3C) from 62 ± 2 s$^{-1}$ to 1.6 ± 0.1 s$^{-1}$.

Stabilization of the early intermediate explains the faster rate of SRP-SR complex assembly with GppNHzp for cargo-loaded SRP (Fig. 2B). Without cargo, formation of the highly labile early intermediate is not sufficient to give a stable SRP-SR complex; to obtain a stable complex, the early intermediate needs to rearrange to the closed complex. However the early intermediate dissociates quickly and less than 2% of the population rearranges to form the closed complex ($k_{off}$ = 62 ± 2 s$^{-1}$ vs. $k_{earr}$ = 1.03 ± 0.02 s$^{-1}$; ref. 14). This gives rise to the slow rate constant for formation of a stable closed complex between free SRP and SR. In contrast, for cargo-loaded SRP the early intermediate is stabilized over 50-fold. Thus forming the early complex (1 step 1) is sufficient to give a relatively stable SRP-SR complex under physiological SRP and SR concentrations (200–400 nM; ref. 23). Furthermore, the cargo/SRP early complex dissociates with much slower kinetics (Fig. 3C, $k_{off}$ = 1.6 ± 0.1 s$^{-1}$), giving this intermediate a much longer lifetime to undergo subsequent rearrangements. Both of these effects contribute to the faster rate of assembling a stable GTPase complex with cargo-loaded SRP in the presence of GppNHzp.

**Cargo Stalls the SRP-SR Complex at Earlier Conformational Stages.**

The different FRET end points in Fig. 2A suggest that the stability of the final SRP-SR complex is also altered by the cargo. To test this hypothesis, we compared the equilibrium stability of the SRP-SR complex assembled in GppNHzp with and without cargo using SRP C235 labeled with acrylodan (Fig. 1 and Fig. S1). Equilibrium titrations using this probe showed that the cargo destabilizes the closed/activated complexes four-fold, increasing its $K_d$ from 10 ± 2 nM to 40 ± 4 nM (Fig. 4A). A similar destabilizing effect was observed using the FRET probes, with the $K_d$ of the closed/activated complexes increasing from 14 ± 3 nM without cargo to 60 ± 7 nM with cargo-loaded SRP (SI Text Fig. S4). An additional probe that specifically monitors the activated complex, acrylodan-labeled SR C356 (Fig. 1 and Fig. S2), also confirmed that the cargo destabilizes the activated complex (Fig. 4B). In summary, the results from all three fluorescence probes showed that, in contrast to the large stabilizing effect of the cargo on the early intermediate, the subsequent conformational changes during the SRP–SR interaction are destabilized by the cargo.

Thus the cargo significantly alters the conformational rearrangements in the SRP-SR complex (Fig. 4C). Without cargo, the closed and activated states are >400-fold more stable than the early intermediate, therefore the equilibrium for the early–closed rearrangement is extremely favorable (Fig. 4C, $K^{rel} = 400–1000$). In contrast, in the cargo/SRP-SR complex, this rearrangement is 200-fold less favorable (Fig. 4C, $K^{rel} = 1.3–22$). Thus, in the cargo/SRP-SR complex, a substantial fraction of the GTPase complex is still in the early conformation (30–40%) even in the presence of GppNHzp. This conformational heterogeneity of the GTPase complex in the presence of cargo is consistent with previous EM analysis that showed that, whereas the SRP is well-resolved in the RNC–SRP complex, upon addition of the SR and GppNHzp, the electron density for both the SRP and SR GTPase domains are no longer visible (24). Thus, both the biochemical and structural analyses highlight the dynamic nature of the GTPase complex when it is bound to the cargo.

The SRP-SR complex can use the early–closed rearrangement to...
drive cargo unloading during protein targeting (Fig. 4D). Initially, cargo loading stabilizes the early intermediate 50-fold (Fig. 4D, $K_d$ and $K_d'$). Correspondingly, the interaction of cargo with the SRP should be stabilized to the same extent in the early intermediate (Fig. 4D, $K_d^{RNC}/K_d^{NC}$). Using the $K_d^{RNC}$ value of $\sim 1$ nM (25, 26), the stability of cargo bound to the early intermediate ($K_d^{RNC}$) to be 20 pM. Although this effect could enhance the initial recognition and delivery of cargo to the membrane, such strong binding will block the subsequent unloading of cargo from the SRP. This problem is circumvented by the 200-fold destabilizing effect of cargo on the early—closed rearrangement (Figs. 4C and D, $K_{d^RNC}$ and $K_{d'NC}$). Correspondingly, the interaction of cargo with the SRP would also be weakened 200-fold by this rearrangement (Fig. 4C, $K_{d''NC}/K_{d''NC}$ = $K_{d''NC}/K_{d''NC}$, thus priming the cargo for subsequent unloading. This model is supported by mutational analyses that showed that mutant GTPases defective in the early—closed rearrangement severely block protein translocation (18). The observation that mutants defective in the closed—activated rearrangement inhibit protein translocation further suggests that this last rearrangement is also essential for cargo unloading (18). Therefore, both rearrangements within the GTPase complex provide essential driving forces to help unload the cargo from the SRP to the PCC, thus initiating protein translocation.

Because cargo disfavors the rearrangements to form the activated complex, one would predict that stimulated GTP hydrolysis, which occurs from the activated complex, would also be impaired. To test this notion, we compared the GTPase reaction rate from the SRP–SR complex in the presence and absence of cargo. In the absence of cargo, the GTPase rate of free SRP is significantly stimulated by the addition of the SR (Fig. 5, circles). The reaction rate reaches a plateau of 0.79 s$^{-1}$ at saturating SR concentrations, representing the GTPase rate constant from the SRP–SR complex (Fig. 5, circles). In the presence of cargo, significantly less GTPase stimulation was observed (Fig. 5, squares). Intriguingly, two plateaus were observed for the GTPase reaction in the presence of cargo (Fig. 5, squares), suggesting the presence of two populations of cargo–SRP–SR complexes: one population, which forms at low SR concentrations (below 50 nM), hydrolyzes GTP at a rate constant of 0.064 s$^{-1}$; the second population, which forms at higher SR concentrations (above 1 μM), hydrolyzes GTP at a rate constant of 0.11 s$^{-1}$ (Fig. 5, squares). Although the nature of this heterogeneity is unclear at present, in both of these populations the GTPase activity is repressed by the RNC (12- and 8-fold for the first and second populations, respectively). The effect of cargo in reducing the GTP hydrolysis rate is specific to the SRP–SR complex as the cargo does not affect the basal GTP hydrolysis rate of the free SRP (SI Text Fig. S5). Thus the cargo also delays GTPase activation in
the SRP-SR complex. This effect, which we term “stalling,” would provide an important time window that allows the SRP to unload the cargo before GTP hydrolysis drives irreversible complex disassembly, as discussed below.

Discussion

We showed here that cargo loading substantially alters the free energy landscape of the SRP–SR interaction cycle (Fig. 6 A). Without cargo (black), assembly of a stable SRP-SR complex is slow because it requires rearrangement from an unstable early intermediate [Fig. 6A, ΔG\text{\text{complex}} = ΔG\text{\text{early}} + ΔG\text{\text{1}}; (14)]. Further, the stable SRP-SR complex has a short lifetime because as soon as it is formed, rapid activation of GTP hydrolysis drives its irreversible disassembly (8). The cargo uses a remarkably simple solution to these problems, by stabilizing the early intermediate (Fig. 6A, ΔG\text{\text{1}} = 1.2 \pm 0.1 \text{kcal/mol}) and disfavoring the closed and activated states (Fig. 6A, ΔG\text{\text{closed}} = 0.8 \pm 0.1 \text{kcal/mol}). This accelerates complex assembly (Fig. 6A, ΔG\text{\text{early}} = 2.4 \pm 0.1 \text{kcal/mol}) and prolongs the lifetime of the SRP-SR complex because of delayed GTP hydrolysis (Fig. 6A, ΔG\text{\text{closed}} = 3.4 \pm 0.1 \text{kcal/mol}). The rate-limiting step of the SRP-SR interaction cycle changes from the early-closed rearrangement with free SRP to GTP hydrolysis with cargo-loaded SRP.

These cargo-induced effects allow the SRP and SR to use each of their conformational rearrangements to regulate a distinct step during protein targeting (Fig. 6B). At the beginning of each targeting cycle, cargo loading (Fig. 6B step 1) allows the SRP to assemble a stable complex with SR > 100-fold faster (Fig. 6B step 2). This ensures rapid delivery of cargo to the membrane (15, 27) and avoids futile interactions between the free SRP and SR. In the early intermediate, the cargo is locked in the SRP-SR complex with very high affinity (Fig. 4D, K\text{SR/complex} = ~20 \text{pM}), allowing the SRP to effectively compete with cellular chaperones for binding the cargo. Subsequent GTPase rearrangements to the closed and activated conformations weaken the interaction of cargo with the SRP (Fig. 6B steps 3 and 4; cf. Fig. 4D) and thus help the SRP to switch from a cargo-binding mode to a cargo-release mode, to unload the cargo to the PCC (Fig. 6B step 4). Once in the activated conformation, and especially after cargo release, rapid GTP hydrolysis drives the disassembly and recycling of both the SRP and SR (Fig. 6B step 5).

The mechanism proposed here (Fig. 6B) focuses on the GTP-bound SRP and SR because the high cellular concentration of GTP compared to GDP (~900 \text{\mu M} and 100 \text{\mu M} in bacteria, respectively) predicts that over 90% of both GTPases are bound with GTP. Minor pathways are also possible in which empty-site or GDP-bound forms of the SRP and SR first form the early intermediate to deliver cargo to the membrane surface, followed by rapid binding or exchange of GTP to drive the subsequent steps (15, 27); these pathways are not depicted in Fig. 6B for clarity.

The most intriguing effect of cargo is “stalling,” that is, the delay of GTPase activation by ~8–12-fold (Fig. 6B step 4). A similar effect was suggested from studies of the mammalian system where before the addition of the PCC, a stable cargo-SRP-SR complex persists in the presence of GTP, suggesting that the cargo may also delay GTP hydrolysis in the mammalian SRP-SR complex (28). We suggest...
that stalling creates an important time window during which the SRP ensures the efficiency and fidelity of protein targeting via either or both of the following mechanisms. First, stalling could provide a spatial checkpoint for the target membrane and/or the PCC. Before the SR associates with the PCC, stalling prevents premature GTP hydrolysis that would irreversibly disassemble the SRP-SR complex and thus help avoid abortive targeting reactions (Fig. 6b step 6). Interaction of SR with the PCC may trigger the rearrangement to the closed and activated states and initiate cargo unloading (28). The PCC also competes with the SR for interacting with the RNC (20, 21, 24, 29), which could further drive the transfer of cargo from the SRP to the PCC (28, 30). Alternatively or in addition, stalling could provide a fidelity checkpoint. Many of the effects of the cargo described here are observed only with RNCs but not with empty ribosomes (SI Text Fig. S6), establishing the importance of the signal sequence. It could be envisioned that cargos with weaker signal sequences could not effectively stall the SRP-SR complex, and thus are more likely to be rejected via premature GTP hydrolysis (Fig. 6b step 6). In this way, GTP hydrolysis could be used to improve the fidelity of protein targeting akin to kinetic proofreading mechanisms used by elongation factor GTPases (31).

Materials and Methods

Materials. The Escherichia coli SRP and SR GTPases (Ffh and FtsY, respectively) and 4.5S RNA were expressed and purified using established procedures (8, 18). Most of the fluorescence experiments used the FtsY (47–49) construct. This truncated FtsY construct behaves similarly to full-length FtsY in its ability to interact with the SRP and to respond to the cargo (SI Text Fig. S3). The GTPase reactions with and without cargo was determined with full-length FtsY. Mutant proteins were constructed using the QuikChange procedure (Stratagene), and were expressed and purified by the same procedure as that for the wild-type protein. Fluorescent dyes DACM, BODIPY-FL, and acrylodan were from Invitrogen. 70S ribosomes and SRP and to respond to the cargo ([157] SI Text 4.5S RNA were expressed and purified using established procedures (8, 18). Most of the fluorescence experiments used the FtsY (47–49) construct. This truncated FtsY construct behaves similarly to full-length FtsY in its ability to interact with the SRP and to respond to the cargo (SI Text Fig. S3). The GTPase reactions with and without cargo was determined with full-length FtsY. Mutant proteins were constructed using the QuikChange procedure (Stratagene), and were expressed and purified by the same procedure as that for the wild-type protein. Fluorescent dyes DACM, BODIPY-FL, and acrylodan were from Invitrogen.

Fluorescence Labeling. For FRET measurements, maleimide derivatives of coumarin and BODIPY-FL were used to label single-cysteine mutants of the SRP and SR, respectively, as described (14). Labeling of the SRP and SR with acrylodan followed the same procedure except that the labeling reaction was carried out using a 30-fold excess of dye over protein for over 12 h at 4 °C. Absorbance of acrylodan (εmax = 20,000 M–1 cm–1) was used to determine the concentration of labeled protein. The efficiency of labeling reaction was typically greater than or equal to 90% for both proteins. The background, estimated from the labeling of the SRP and SR lacking cysteines using the same procedure, is less than 3%.

Fluorescence Measurement. All measurements were carried out at 25 °C in assay buffer [50 mM K/Hepes, pH 7.5, 150 mM KCl, 10 mM Mg(OAc)2, 2 mM DTT, 0.1% (v/v) BSA] on a Fluorescence Spectrometer (Jobin Yvon) as described (15, 14). FRET measurements were carried out using an excitation wavelength of 380 nm and an emission wavelength of 470 nm. FRET efficiency was calculated as described (14). Fluorescence emission spectrum of the SRP (or SR) labeled with acrylodan was measured using an excitation wavelength of 370 nm. Fluorescence emission at 500 nm was monitored for equilibrium titrations using acrylodan-labeled protein.

Pulse–chase experiments were carried out using unlabeled protein to trap any dissociated SRP or SR (10). Fast reactions were measured on a Kintek stop-flow apparatus (10). The time interval during equilibrium measurements was calculated based on the SRP-SR complex assembly rate (10, 14), and varies from 5 min for fast reactions (early complex assembly and complex assembly in the presence of cargo) to several hours (complex assembly with GppNppG in the absence of cargo).

GTase Assay. The GTase assay to measure the stimulated GTP hydrolysis reaction between the SRP and SR were carried out and analyzed as described (8). Multiple turnover reactions were carried out at 25 °C with a small, fixed amount of GTP and increasing concentrations of SR; 100 μM GTP (doped with trace [3P]GTP) was present in the reaction to saturate both GTase sites. The data presented in Fig. 5 was representative of four experiments. Previous studies have established that the GTase reaction rate is rate-limited by SRP-SR complex formation at sub-saturating SR concentrations, whereas at saturating SR concentrations, the reaction is rate-limited by GTP hydrolysis or a slow conformational change preceding GTP hydrolysis (8). The release of products, including dissociation of GTP from the SRP-SR-GDP complex, are not rate-limiting in this GTase assay (8).

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Supporting Information

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SI Methods

Preparation of 70S Ribosomes and RNCs. 70S empty ribosomes were purified from E. coli MRE600 following a modified protocol described by Moazed and Noller (1). Cell pellet from a 1-L culture was resuspended in 30 ml buffer A [20 mM Tris/HCl (pH 7.0 at 21 °C), 10.5 mM MgCl₂, 100 mM NH₄Cl, 0.5 mM EDTA, 6 mM 2-mercaptoethanol (β-ME)]. The cell resuspension was passed through the French Press twice to lyse the cells. The lysate was clarified by two rounds of centrifugation at 20,000 × g for 15 min at 4 °C. The supernatant was layered on a 1.1-M sucrose cushion in buffer B [20 mM Tris/HCl (pH 7.0 at 21 °C), 10.5 mM MgCl₂, 500 mM NH₄Cl, 0.5 mM EDTA, 6 mM β-ME, and 1.1 M sucrose] and ultracentrifuged at 100,000 × g for 21 h at 4 °C. The ribosome pellet was collected and dissolved in buffer A containing 500 mM NH₄Cl. The dissolved ribosomes were ultracentrifuged at 4 °C for 3 h at 100,000 × g. The pellet was dissolved in buffer C [20 mM Tris/HCl (pH 7.0 at 21 °C), 6 mM MgCl₂, 100 mM NH₄Cl, and 6 mM β-ME], layered on top of 32 ml sucrose gradients [10–40% (w/v) sucrose in buffer C], and ultracentrifuged at 50,000 × g for 14 h at 4 °C. Fractions containing 70S ribosomes were collected and ultracentrifuged at 100,000 × g for 17 h at 4 °C. Ribosome pellets were collected and dissolved in storage buffer [20 mM Tris/HCl (pH 7.0 at 21 °C), 10 mM MgCl₂, 100 mM NH₄Cl, and 6 mM β-ME]. Ribosomes were stored at −80 °C.

The RNC was generated from in vitro translation in a membrane-free cell extract prepared from E. coli MRE600 as described (2). In vitro translation was performed at 37 °C for 25 min. The translation mix was layered onto a 40 ml sucrose gradient in buffer S1 [10–50% (w/v) sucrose in 50 mM HEPES-KOH (pH 7.5 at 4 °C), 100 mM Mg(OAc)₂, 100 mM NH₄Cl] and ultracentrifuged at 4 °C for 15 h at 23,500 rpm using a SW-32 rotor (Beckman). Fractions containing monoribosome were collected and loaded onto a 1-mL Strep-Tactin Sepharose column (IBA) equilibrated with buffer S1 at 4 °C. Buffer S1 containing 2.5 mM desthiobiotin (Sigma) was used to elute RNCs from affinity column. RNC-containing fractions were centrifuged at 55,000 rpm for 3 h at 4 °C using a TLA-55 rotor (Beckman). Pellets were collected and dissolved in buffer S1 with 25 mM Mg(OAc)₂.

Fig. S1. Acrylodan labeled SRP C235 monitors formation of the closed/activated conformation. Fluorescence emission spectra are acquired in the presence of 
GppNHp for acrylodan-labeled SRP C235 alone (0.1 μM; black), labeled SRP C235 incubated with 1 μM wild-type SR (blue), or labeled SRP C235 incubated with 
1 μM SR A335W (red), which is blocked in the closed—activated rearrangement and thus isolates the closed complex (3), or in the presence of GDP with 10 μM 
SR (green), which isolates the early complex (4).
Acrylodan labeled SR C356 specifically monitors formation of the activated SRP-SR complex. (A) Fluorescence emission spectra was obtained for acrylodan labeled SR C356 alone (0.1 μM; black), acrylodan-labeled SR C356 incubated with wild-type SRP (blue) or SRP A144W (red) in the presence of GppNHp, or with 10 μM SRP in the presence of GDP (green). SRP A144W allows a stable closed complex to form but specifically blocks formation of the activated complex (5). The absence of fluorescence change with SRP A144W shows that acrylodan-labeled SR C356 specifically monitors formation of the activated complex. (B) Acrylodan-labeled C356 does not change fluorescence if mutant SR A355W (3) was used to block the formation of the activated complex. Spectra was obtained for 0.1 μM acrylodan-labeled SR A355W/C356 alone (black) and when this labeled SR mutant was incubated with 1 μM SRP in the presence of GppNHp (red) or with 5 μM SRP in the presence of GDP (green). The absence of a fluorescence change shows that the probe on SR T356 does not detect the early or the closed complex.
Fig. S3. Full-length FtsY behaves similarly to FtsY (47–497) in its ability to respond to the cargo. (A) Cargo accelerates SRP-SR complex assembly with GppNHp by 400-fold when full-length FtsY is used. The data were obtained with 20 nM SRP, 100 μM GppNHp, and varying concentrations of full-length FtsY in the presence and absence of 60 nM RNC. The data were analyzed as in Fig. 2B and give association rate constants ($k_{on}$) of $1.3 \times 10^7 M^{-1}s^{-1}$ and $3.3 \times 10^4 M^{-1}s^{-1}$ with (●) and without (●) 60 nM RNC, respectively. (B) The early complex formed with full-length FtsY is stabilized significantly by the cargo, as was observed with FtsY (47–497). Equilibrium titration of the early complex was carried out in the absence of GppNHp with 50 nM RNC. Nonlinear fits of data gave $K_d$ values of $85 \pm 5$ nM, which is comparable to the value of $80 \pm 4$ nM obtained with FtsY (47–497) (Fig. 3B, squares).
Equilibrium titration of the SRP-SR complex assembled in GppNHp with (●) and without (○) RNC using the FRET assay. Nonlinear least squares fits of data gave $K_d$ values of 14 ± 3 nM (without RNC) and 60 ± 7 nM (with RNC). For the cargo-loaded SRP, an accurate determination of the stability of the closed/activated states by FRET is complicated by the fact that the stabilities of the SRP-SR complexes assembled with and without GppNHp are very similar (60 vs. 80 nM, respectively); thus, a significant fraction of the SRP•SR complex is in the early conformation even in the presence of GppNHp. The observed affinity of the cargo-SRP-SR complex of 60 nM is consistent with the weighted average of the stabilities of the early intermediate (80 nM, Fig. 4C) and the closed complex (40 nM, Fig. 4C) that are equally populated in the presence of GppNHp and cargo.
The RNC does not significantly affect the basal GTPase reaction of the free SRP. The basal GTPase reactions were carried out under single turnover conditions with trace $\gamma^{32}$P-GTP ($<0.1$ nM) and varying concentrations of SRP. Linear fits of the data give $k_{cat}/K_{m}$ values of $1.4 \times 10^{5}$ M$^{-1}$min$^{-1}$ and $1.2 \times 10^{5}$ M$^{-1}$min$^{-1}$ in the absence (●) and presence of RNC (○), respectively.
Fig. S6. Empty ribosomes do not substantially alter the interaction between the SRP and SR. (A) The time course for SRP-SR complex formation, monitored by FRET, in the absence (black) and presence (red) of 0.8 μM ribosomes. Data were obtained with 0.1 μM SRP, 1.0 μM SR, and 100 μM GppNHp. (B) The ribosome accelerates disassembly of the SRP-SR complex approximately 4-fold. The rate constants for complex disassembly were determined in the absence (black) and presence (red) of 1.0 μM ribosomes. Fits of the data to single exponential decay give dissociation rate constants of 0.010 ± 0.003 s⁻¹ and 0.0027 ± 0.004 s⁻¹ in the presence and absence of ribosome, respectively. (C) The ribosome does not affect the rate of SRP-SR complex assembly. Association kinetics of the SRP-SR complex was measured as in Fig. 2 with (●) or without (○) 1.0 μM ribosome. Linear fits of the data gave $k_{on}$ values of $(4.7 \pm 0.7) \times 10^{4}$ M⁻¹ s⁻¹ with ribosome and $(4.7 \pm 0.4) \times 10^{4}$ M⁻¹ s⁻¹ without ribosome, and $k_{off}$ values of 0.011 ± 0.004 s⁻¹ with ribosome and 0.002 ± 0.003 s⁻¹ without ribosome. (D) Ribosome does not stabilize the early intermediate. FRET values are compared for SRP-SR early complex assembled with GDP in the presence and absence of ribosome. Data were obtained with 0.1 μM SRP, ribosome, and 1.0 μM SR. GNP denotes GMPPNP. (E) Ribosome does not substantially affect the stimulated GTP hydrolysis in the SRP-SR complex. GTPase rate constants were measured and analyzed as described in SI Methods using 15 nM SRP and 50 μM GTP in the absence (○) and presence (●) of 1.0 μM ribosome.