Structure of hibernating ribosomes studied by cryoelectron tomography in vitro and in situ

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Ribosomes arranged in pairs (100S) have been related with nutritional stress response and are believed to represent a “hibernation state.” Several proteins have been identified that are associated with 100S ribosomes but their spatial organization has hitherto not been characterized. We have used cryoelectron tomography to reveal the three-dimensional configuration of 100S ribosomes isolated from starved Escherichia coli cells and we have described their mode of interaction. In situ studies with intact E. coli cells allowed us to demonstrate that 100S ribosomes do exist in vivo and represent an easily reversible state of quiescence; they readily vanish when the growth medium is replenished.

Introduction

An early description of E. coli 70S ribosomes reported that these particles were frequently found associated in pairs, later referred to as 100S ribosomes (Tissieres and Watson, 1958). It was subsequently observed that the formation of 100S ribosomes occurs in stationary phase (Wada, 1998). The 100S ribosomes are distinct from disomes (two ribosomes linked by mRNA) in that they are not translationally active, but represent a storage form or hibernation state (Wada et al., 1995). The ribosome modulation factor (RMF), and the hibernation promoting factor (HPF, previously known as YhbH), are known to be involved in the formation and maturation of these ribosome dimers, respectively, whereas YfiA (protein Y) is suggested to bind 70S ribosomes in stationary phase (Wada et al., 1990; Maki et al., 2000). Some aspects of the interaction of these factors with the translational machinery have been explored in recent years (Ueta et al., 2005, 2008; Yoshida et al., 2009), but the interpretation of these data has been hampered by the lack of a detailed 3D structure of 100S ribosomes.

X-ray crystallography and EM single-particle analysis have provided unprecedented insights into the molecular architecture of ribosomes and have been instrumental in elucidating key events during translation (for review see Schmeing and Ramakrishnan, 2009). Both techniques rely, more or less, on homogeneous samples of ribosomes, ideally trapped in a particular functional state. Other higher-order structures, such as polysomes, display a degree of plasticity in their supramolecular organization, which makes them intractable to x-ray crystallography or single-particle analysis. Cryoelectron tomography (CET; Lucic et al., 2005) can complement these techniques by allowing the visualization of variable or flexible molecular structures both in vitro and in situ (Ortiz et al., 2006), i.e., in the functional environment of intact cells. Although the resolution is considerably lower than that achieved by x-ray and single-particle cryo-EM, computational analysis of subtomogram volumes opens the way for hybrid approaches to interpret the tomograms in the light of preexisting high resolution structures. In the past, we have used such an approach to study the native 3D organization of E. coli ribosomes in densely packed polysomes (Brandt et al., 2009).

Here, we report a structural study of ribosomal dimers (100S) by CET, both in ribosome-enriched fractions from starved E. coli cells and in intact cells cultured in minimal medium.
Variability of isolated ribosomal assemblies

Initially, 100S ribosomes were investigated in vitro, i.e., in diluted cell lysates in which nonspecific interactions are reduced. Cell lysates can be examined in relative thin (50–200 nm) ice layers compared with the much thicker ice layers (>0.5 µm) needed for embedding cellular structures. The thicker ice layers result in a degradation of image quality. Tomograms were acquired from frozen-hydrated samples derived from E. coli cells grown to starvation in which clusters of ribosomes with a variable number of 70S particles could be observed (Fig. 1 A). Visual inspection of the tomograms showed that 20–25% of the 70S ribosomes formed dimers (Fig. 1 D), which associate via their small subunits (30S), in agreement with earlier 2D studies of stained samples (Wada, 1998; Yoshida et al., 2002). This number might well be an underestimate of the abundance of 100S ribosomes, given the fact that the 100S particles easily dissociate into monomeric ribosomes. The remaining ribosomal particles were individual 70S ribosomes or clusters of three or more ribosomes in close proximity. The ribosomes forming trimers also appeared to associate via the 30S subunits.

We performed a 3D analysis of the tomographic data using template matching for an initial determination of the relative positions and orientations of the 70S ribosomes (Frangakis et al., 2002). A reference density map derived from the crystal structure of an E. coli ribosome (Schuwirth et al., 2005) was used as a template to detect and align individual ribosomes (Fig. S1). Replacement of individual ribosomes by the template in the orientation determined for the given ribosomes confirmed the proximity of small ribosomal subunits (Fig. 1, B and C). The position and orientations determined by template matching were used for the 3D analysis of center-to-center vector distances between neighboring ribosomes. This analysis provided an objective characterization of the spatial organization of ribosomes. The two 30S subunits of each dimer are in close proximity, but their relative orientation is more variable than in stalled polysomes where the densely packed ribosomes are found in two clearly preferred relative orientations (Fig. 1, E and F; Brandt et al., 2009). The association of ribosome pairs isolated from starving cells seems to have a higher degree of translational and rotational freedom around the contact sites, which are located between the entry and exit sites of the mRNA on the 30S subunits. We determined an average center-to-center spacing of 25.6 nm for neighboring ribosomes in the tomograms of starved cell lysates, a larger separation than the 21.6 nm found previously with stalled polysomes (Brandt et al., 2009).

When all the subtomograms containing monomeric, dimeric, as well as trimeric ribosomes were aligned with a 70S ribosome reference and averaged, the resulting density map showed a 70S particle with some additional blurred density around the 30S subunit, but no well-defined density corresponding to a second 70S particle as would be expected for a rigid and well-defined ensemble (Fig. 2 A). But this is not surprising given the low abundance of dimeric ribosomes in the sample (see above) and the flexible nature of the linkage between monomers, discernible already in the raw data.

To verify the identification of ribosomes in selected subtomograms and their correct localization in 3D space, a subset of subtomograms was aligned in a completely unsupervised manner using a novel, reference-free maximum-likelihood refinement algorithm for 3D images with missing data regions in Fourier space (Scheres et al., 2009). The refined model was almost indistinguishable from the one obtained using alignment based on template matching (Fig. 2 F). The similarity between the models proves that the use of a reference in the template-based approach does not introduce a bias in this case.

Next, we applied successive steps of classification to the data using constrained correlation ( Förster et al., 2008; Fig. 2, B–E). Dimer-only class averages created from independent sample pools clearly showed density for both 70S particles (Fig. 2, C and D). It was reassuring to see that the result obtained with template matching and the nonsupervised alignment and
In a 70S ribosome, the surface of the 30S subunit that is opposed to the inter-subunit space is commonly referred to as the cytosolic face (Fig. S1, “front” view). In the refined structure of the 100S ribosome, the cytosolic faces of the two 30S subunits are juxtaposed (Fig. 3 A). We denote this arrangement as “front-to-front” (f-f; Fig. 3 B). The pairing in the structure derived from hibernating ribosomes is quite different from the one found in stalled polysomes in vitro, called “top-to-top” (t-t; Fig. 3 B).
Rigid-body docking of two copies of the *E. coli* 70S ribosome structure into the dimer density map revealed possible interacting ribosomal components (Fig. 3, C and D). Two major contact regions between the small subunits of the dimers could be distinguished (Fig. 3 E). The first (I) involves proteins S9, S10, and the 16S rRNA helix 39 (Fig. 3, F and G). The second region (II) appears to involve the S2 protein because this protein is localized in the docked crystal structure adjacent to the density in the region II and it was found outside the density map envelope (Fig. 3, H and I). It has been suggested that S2 contacts the mRNA during movements associated with translation, and therefore displays a high degree of flexibility (Yusupova et al., 2006).

The f-f dimer average has additional density corresponding to a mass of approximately 25 kD associated with the small ribosomal subunit, in a region close to the mRNA tunnel exit and the so-called platform (Fig. 3, A and C). At the present resolution, it was not possible to assign any of the factors reported as being associated with 100S ribosomes, such as RMF (6 kD) and HPF (10.8 kD), unambiguously to these densities. It is in fact unlikely that the additional density associated with the 30S subunit is due to these factors. RMF has been shown to bind the large ribosomal subunit (50S) in a region close to the peptidyl transference center (Yoshida et al., 2002, 2004; Fig. 3, F and G). HPF shares 40% sequence homology with YfiA (12.7 kD; Ueta et al., 2005) and adopts an overall structure similar to YfiA (Sato et al., 2009). HPF has been suggested to bind to the peptidyl-tRNA site (P-site) and aminoacyl-tRNA site (A-site) of the 30S subunit, similar to where YfiA is known to dock (Vila-Sanjurjo et al., 2004; Fig. 3, F and G).

Additional proteins associated with 100S ribosomes

In an attempt to identify additional nonribosomal proteins bound to dimers, we analyzed crude ribosomal fractions isolated from starved *E. coli* by mass spectroscopy. Several candidate proteins were detected, including RMF, HPF, and YfiA, and several other ribosome-binding proteins, such as the stationary phase–induced ribosome-associated protein (SRA, 5 kD), the ribosome-dependent endonuclease RelE, and initiation and elongation factors (Table S1). At this stage, we have not yet been able to discriminate between factors that associate with 100S ribosomes, but not with 70S ribosomes, nor could we assign any of the candidate proteins to the extra density found on the 30S subunits. Future studies with tagged ribosomes allowing for a better purification and cross-linking approaches in conjunction with mass spectrometry should enable us to identify specific interactors and correlate them with the observed density.

Consistent with the suggested function of HPF in blocking tRNA binding in the A- and P-sites, we have not found densities in the canonical tRNA positions, even at low intensity thresholds. Given that the platform has been described as a center for translational regulation (Marzi et al., 2007), we consider a potential participation of structured mRNAs or other RNA molecules in the 30S-associated density present in the 100S ribosomes.

While this manuscript was under revision, Kato et al. (2010) published an article describing the structure of isolated...
Thus, we aimed at identifying 100S particles in situ by CET of intact *E. coli*. Cells grown in rich media have an average diameter of ~1 µm, which is too thick for a reliable identification of most macromolecules. Slow growth in minimal medium results in cells with a diameter of ~400 nm (Woldringh et al., 1977), improving tomogram quality significantly and thereby facilitating the recognition of macromolecular complexes. We recorded tomograms of *E. coli* cells grown in minimal media up to mid-exponential and stationary phases (Fig. 4, A–E) and analyzed the resulting ribosome distribution (Fig. 4, F–G; Fig. S2). We found that only cells grown to stationary phase can be observed. Two ribosome copies are clearly distinguishable in an XY slice (I) and the isosurface representation of an average of 878 subvolumes containing ribosome dimers extracted from tomograms of *E. coli* in stationary phase (J).

**Figure 4. 100S Ribosomes identified in situ.** (A) Slice of a tomogram of an intact *E. coli* cell grown in minimal media (bar, 100 nm). Longitudinal (B) and transversal (C) views of corresponding isosurface representation. Models of 70S ribosomes with colored 30S (yellow) and 50S subunits (blue) are positioned where ribosome dimers were detected. The inner and outer membranes were manually segmented (dark and light brown, respectively), and were the basis of a membrane model (black grid). Manually segmented Pili are depicted in green. (D) A magnified tomographic section through a single ribosome dimer. (E) Surface rendering of a model ribosome dimer replacing the ribosomes shown in D (bar, 50 nm). (F–H) x-y plots of center-to-center 3D distance vectors between each ribosome and its closest ribosome neighbor. Plots correspond to representative tomograms for three different growth conditions: exponential phase (F), stationary phase (G), and grown to stationary phase but supplemented with amino acids (H). Filled dots correspond to particles clustered based on center-to-center vectors and relative orientations, circles represent single ribosomes. Only in stationary phase can a distinct cluster be observed. Two ribosome copies are clearly distinguishable in an XY slice (I) and the isosurface representation of an average of 878 subvolumes containing ribosome dimers extracted from tomograms of *E. coli* in stationary phase (J).

**Existence of 100S ribosomes in situ**

The existence of ribosome dimers in vivo has remained a controversial issue because it cannot be ruled out that the ionic conditions of the working buffer could favor nonspecific interactions. Thus, we aimed at identifying 100S particles in situ by CET of intact *E. coli*. Cells grown in rich media have an average diameter of ~1 µm, which is too thick for a reliable identification of most macromolecules. Slow growth in minimal medium results in cells with a diameter of ~400 nm (Woldringh et al., 1977), improving tomogram quality significantly and thereby facilitating the recognition of macromolecular complexes. We recorded tomograms of *E. coli* cells grown in minimal media up to mid-exponential and stationary phases (Fig. 4, A–E) and analyzed the resulting ribosome distribution (Fig. 4, F–G; Fig. S2). We found that only cells grown to stationary phase have a fraction (10–20%) of identified ribosomes with neighboring 70S particles in the spatial arrangement described above as characteristic for 100S ribosomes (Fig. 4 G vs. Fig. 1 E). Interestingly, the clustering found in the cellular tomograms is indicative of a lower degree of variability in the relative orientation of the two monomers of the 100S ribosome in situ than in the in vitro preparations. Shear forces acting upon the particles during isolation might well cause distortions of the weakly connected monomers. Under conditions of exponential growth in minimal media we observed neither clustering indicative of dimers nor of...
polysomes (Fig. 4 F), possibly because initiation events are rare under these conditions. It is known that the inhibition of ribosomes by RMF and consequent ribosome dimerization is reversible, as the 100S ribosomes dissociate back into 70S ribosomes within 2 min upon transfer of starved cells into fresh media (Wada et al., 1990; Yoshida et al., 2002). We tested whether the ribosomal clustering observed in stationary phase would vanish when supplying fresh nutrients. Indeed, no clustering of ribosomes was detected when cells previously grown to stationary phase in minimal media were supplemented with amino acids or transferred to rich media (Fig. 4 H). Moreover, a low resolution model of the f-f ribosome dimer was generated by averaging a subset of 70S ribosomes from tomograms of cells in stationary phase identified by classification as having a second ribosome attached (Fig. 4, I and J). The results confirm the physiological relevance of the f-f ribosome dimers observed in fractions from cell lysates and further support their association with nutritional stress.

**Discussion**

Our understanding of ribosomal clustering coupled to growth-phase transitions is summarized in Fig. 5. Stalling of ribosomes during translation is not unusual, and it can be caused, among other reasons, by secondary mRNA structures, rare codons, or amino acid scarcity (Buchan and Stansfield, 2007). Stalled ribosomes can be recycled by at least two different mechanisms: in the case of truncated messengers, by the tmRNA system or in the case of ribosomes stalled at the stage of elongation, by the initiation factor 3 (IF3) and the ribosome recycling factor (RRF; Singh et al., 2008). The synthesis of stable RNA species in many *E. coli* strains is sharply decreased by deprivation of amino acids. This response is predominantly regulated by the guanosine pentaphosphate or tetraphosphate [(p)pGpp]. The level of (p)pGpp in bacteria is controlled by two ppGpp synthetases (PSI/PSII), encoded by the relA and spoT genes (Murray and Bremer, 1996). The binding of uncharged tRNAs to the ribosomes is a signal for activation of the ribosome-bound PSI. The accumulation of (p)pGpp reduces the synthesis of additional ribosomes and thereby reduces the consumption of amino acids; this in turn allows the remaining ribosomes to function at a higher rate (Bremer and Dennis, 2008). The transcription of the *rmf* gene is positively regulated by (p)pGpp (Izutsu et al., 2001).

The inhibition of translation by ribosome–dimer formation during starvation has been attributed primarily to RMF binding, although the role of the RMF in the dimerization process is not yet well understood. The action of RMF might resemble the inhibition of translation by certain antibiotics (Yoshida et al., 2002). In more recent studies, it has been suggested that RMF promotes the formation of a 90S complex, which matures with the addition of HPF to form the 100S particle (Fig. 5, C and D; Ueta et al., 2005). Interestingly, the proteins S9 and S10, which are located in the contact region I of the f-f 100S dimers, have domains (C-terminal in S9 and R45-H70 in S10) extending to a site close to the probable HPF binding site (Fig. 3, F and G). A conformational change induced by HPF or YfiA at the tRNA binding sites could be propagated through the head of the 30S subunit, altering its affinity for another 30S subunit.

Our experiments proved that the 100S ribosome complex is a distinct biologically relevant ribosomal assembly in *E. coli* cells under conditions of nutritional stress. This is in agreement with biochemical studies reporting the appearance of ribosome dimers (Wada, 1998; Ueta et al., 2008). Mutants with a disrupted *rmf* gene do not form ribosome dimers and lose viability earlier than wild-type cells in stationary phase (Yamagishi et al., 1993; Wada et al., 2000). Due to the antagonistic functions of HPF and YfiA, mutants with single deletions in the corresponding genes live slightly longer than wild type (Ueta et al., 2005). These effects on cell survival have been interpreted in terms of ribosome protection against degradation, as the free 50S and
30S subunits, not the 70S particles, are the targets for endoribo-
nuclease action and ultimately degradation (Zundel et al., 2009).
Stalled ribosomes can be recovered by the tRNA system or
IF3/RRF interactions causing the release of truncated nascent
chains. However, with reduced availability of nutrients, the in-
activation of a portion of available ribosomes by RMF/HPF
could alleviate the problem of stalling during the transition to
stationary phase.

Although active 70S ribosomes are thought to be rare in the
stationary phase, the blocking of tRNA binding sites in dimerized
ribosomes might allow an effective use of limited aminoacl-
tRNAs for the remaining active ribosomes. Thus, ribosome di-
merization might have a dual role in protecting ribosomes against
degradation, allowing rapid recovery of translation, and facilitat-
ing protein synthesis under stringent conditions by reducing com-
petition for scarce resources (Fig. 5 D). The association of the
100S ribosomes with a variety of factors required for translation
may allow these complexes to rapidly resume protein synthesis
once more favorable nutrient conditions have been established.
Our results provide a model for the interactions of hibernating
ribosomes, which can help to direct further biochemical experi-
ments leading to a fuller understanding of the processes underly-
ing their formation.

Materials and methods

Cell cultures

Overnight cultures of E. coli (ECOR48) cells in LB medium (0.5 ml) were
inoculated into 1 L of medium E (Vogel and Bonner, 1956) supplemented
with 2% Bacto-Trypton (Becton Dickinson) and 0.5% glucose at 37°C with
shaking at 100 cycles per min during 3 d. These growing conditions are
reported to give maximal stationary phase survival for most E. coli strains
(Wada et al., 2000). For ribosome isolation, cell pellets were stored at
−80°C until use. E. coli (B/r k) was grown in M9 minimal medium sup-
plemented with 0.03% (wt/vol) alanine (as the sole carbon source) up to
mid-exponential and stationary phase (optical density at 600 nm of 0.08
and 0.17, respectively). Cell suspensions were concentrated to an optical
density at 600 nm of 0.5 by centrifugation. Stationary phase suspensions
were supplemented with 40 µg/ml each amino acid (equi-mass concentra-
tion) or LB. For C1, cultures were used immediately after reaching the de-
sired optical density.

Preparation of crude ribosomes

Preparation of crude ribosomes from E. coli (ECOR48) or E. coli (B/r k)
was performed according to the method of Noll et al. (1973) with slight modifi-
cations (Horie et al., 1981). Cells were grown with 2.5 volumes of aluminum
oxide (type A-5; Sigma-Aldrich) and extracted with buffer I (20 mM Tris-HCl,
PH 7.6, 15.2 mM (CH3COO)2Mg, 0.8 mM EDTA, 100 mM CH3COONH4, and
3 mM DTT) containing RNase-free DNase I at 2 µg/ml. Lysates were
centrifuged at 18,000 rpm (~30,000 g) for 30 min at 4°C on a rotor (model
75Ti; Beckman Coulter). The supernatant was separated on 75% (v/v)
sucrose from monosomes or other complexes, but we avoided further purifica-
tion steps to prevent possible dissociation of ribosomes.

Mass spectrometry analysis

1 µg crude ribosomal samples were reduced and alkylated (using DTT and
iodoacetamide, respectively) and in-solution digested ON using trypsin.
The resulting digest was desalted and concentrated on a StageTip followed
by speed-vaccing (Rappsilber et al., 2003, 2007). The samples were ana-
lized on an LTQ-Orbitrap (Thermo Electron) with a nanoPump (model 1010,
Agilent Technologies) and an HTC PAL autosampler. The nanoPump deliv-
ered a 140-min gradient (5–80% ACN) to a silica emitter packed with a
C18-column for reverse-phase separation. Data were acquired using a
scan cycle of one full scan MS in the FT (Orbitrap) followed by (up to) six
iontrap MS2 scans (LTQ) of the six most intense peaks in the full scan. The
acquired MS data were searched against the E. coli sequences of SwissProt
release 57 using Mascot v 2.2 (Matrix Science) and processed using
MaxQuant v 1.0.13.13 (Cox and Mann, 2008) with an FDR of 1% (peptide and
protein) for the protein list.

Cryoelectron tomography

Dialyzed ribosomal fractions were applied to R2/2 Quantifoil grids (Quantifoil),
previously incubated with 10-nm colloidal gold markers. 5 µl of the
E. coli (B/r k) suspensions were applied to R2/1 Quantifoil grids (Quantifoil),
followed by 1 µl of colloidal gold (10 nm, protected with BSA). After blotting
with filter paper, the grids were vitrified in liquid ethane and stored until
usage in liquid nitrogen. For lysisates, 26 single-axis tilt series were recorded
using a CM20 FEG transmission electron microscope (FEI) operating at
160 kV, a 4096 × 4096 slow-scan CCD camera, and control software for
automated image tracking and focusing (TVIPS). The angular range used was ±60°,
sampled with angular increments of 3°; and with a cumulative electron dose not exceeding 50 e−/Å2. Images were collected using a nomi-
nal 3-nm defocus. The effective magnification was 54,000, which re-
sulted in a pixel size of 0.28 nm for the unprocessed images. Alignment was
facilitated by the use of selected gold particles. For 3D reconstruction the im-
ages were weighted and back-projected using the Tom software package
[Nickell et al., 2005]. For cellular CET, tomography data were collected in a
cryo-transmission electron microscope (T30 Polara; FEI) equipped with a
field emission gun operated at 300 kV. Zero-loss energy filtered images were
taken with a 2048 × 2048 Multiscan CCD camera (Gatan) at the end of a
GIF 2000 post-column energy filter (Gatan). Tomograms were collected at
final magnification of 42105 (giving a pixel size of 0.713 nm at the speci-
fics level) and using a 9 µm defocus, a tilt range of ±60°, and an angular
increment of 1.5°. Alignment and reconstruction were performed using the
IMOD software package (Kremer et al., 1996). The number of tomograms
analyzed for exponential phase, stationary phase, and aa-supplemented
stationary phase was 5, 6, and 4, respectively.

Template matching

For detection of the 70S ribosomes on recorded tomograms, down-sampled
reconstructed volumes (2.24 nm/voxel for tomograms of ribosomal frac-
tions and [1.4] nm/voxel for cellular tomograms) were cross-correlated
with a template structure using the program MOLMATCH (Franquèks et al.,
2002; Ortiz et al., 2006). The 3D template was generated from 3.5 Å crys-
tal structures of the E. coli ribosome (PDB entries 2AW7 and 2AWB;
Schuwirth et al., 2005), adjusting pixel size and bandpass filtered to 4 nm
(Fig. S1). The cross-correlation function (CCF) was calculated rotating the
template over all Euler Angles with 1° increments. A large number of parti-
cles i with the highest cross-correlation coefficients (CCCs) found were local-
ized in each tomogram extracting the 3D coordinates (x, y, z) and Euler angles
ψ, θ, φ describing the relative orientation of the best sampled relative orientation
of the particle i with respect to the reference. The Eulerian angles ψ, θ, and φ used
in this study are defined by clockwise rotations about the z-, x-, and again
z-axes of a right-handed static coordinate system x, y, and z, respectively
[Nickell et al., 2005; Brandt et al., 2009]. These conventions are exem-
plified with the rotated 70S ribosome map used as reference in Fig. S1.

Averaging and classification of subtomograms

Selected particles were reconstructed in subtomograms with lower binning
factor ([0.56 nm]2/voxel for tomograms of ribosomal fractions and
[0.7 nm]2/voxel for cellular tomograms) and 3D aligned against a 4-nm
resolution 70S ribosome reference properly scaled as described previously
(Förster et al., 2005; Brandt et al., 2009). 3D alignments and 3D averaging
was performed with the use of AV3 (Förster and Hegelr, 2007; Förster et al.,
2008). After recognition of putative ribosomes using template matching,
subsequent discrimination of false positives was addressed by classification
of subvolumes using a constrained-correlation method (Förster et al., 2008)
in which the search of similarity between particle pairs was restricted to the
volume to be occupied by only one centered ribosome i, applying an spheri-
cal mask of 14-nm radius. The number of classes was set as high as possible,
such that each class contained a small number of particles (at least 20 parti-
cles in order to increase the signal of tomograms by one order of magni-
tude). Averages of classified particles were calculated for each class.
Particles contributing to averages not consistent with the ribosome structure
were discarded. Thus, 601 particles for tomograms of the Pool 1, and 1,232
particles of Pool II, were identified as bona fide ribosomes.

Structure of hibernating ribosomes • Ortiz et al. 619
A second step of classification used the same constrained-correlation algorithm but considering only areas surrounding each identified (centered) ribosome in a sphere of 30 nm. Thus, ribosomes pairs with F orientation were identified. Ribosomes in each dimer with higher similarity to an initial average map were selected to contribute to the same position in the dimer during iterative alignment steps. Thus, 35 dimers (~1% of identified 70S ribosomes) from Pool II were averaged.

The analysis of the relative spatial relationship between particles was performed as previously for polysomes (Brandt et al., 2009) with slight modifications. In brief, distances between the center of mass of each detected ribosome i and its nearest neighbor j were calculated. A vector for ribosome i was calculated relative to the coordinates of the reference. Relative euclidian distances and relative angles were hierarchically clustered, using the sum of pairwise dot products as metric. The relative angles were transformed into quaternion space before calculating dot products between pairs of quaternions and back-transformed into Eulerian space for display of clustered rotations. In an alternative classification approach to the constrained-correlation based, we classified particles using this hierarchically clustering of relative localization and orientation.

Resolution of density maps were determined by Fourier shell correlation of two averages each derived of half of the pertinent particles.

Reference-free alignment
The subset of 601 particles from Pool I were aligned in a completely unsupervised manner using a novel, reference-free maximum-likelihood refinement algorithm for 3D images with missing data regions in Fourier space (Scheres et al., 2009). Precentered particles were windowed to 60 × 60 × 60 voxels in order to contain a single ribosome at the center of each particle. An unbiased initial model for the iterative maximum-likelihood refinement algorithm was obtained by assigning random orientations to all particles, resulting in a relatively featureless blob of density. This model was refined during 12 iterations with an angular sampling rate of 12 degrees, followed by 3 more iterations with an angular sampling rate of 9 degrees and restricting the integrations over the angles by ±32 degrees around the optimal angles from the 12th iteration.

Reference-free classification
Unsupervised classification was done using the same 3D maximum likelihood approach, but using the particles without windowing. Unbiased starting models were generated by calculating the average of three random subsets of the particles in random orientations. The resulting models were refined simultaneously against the entire dataset during 25 iterations and using an angular sampling rate of 15 degrees. During the first 5 iterations similarity between the three references was imposed as described previously (Scheres et al., 2009). A smaller spread of ribosome dimer orientations could also be obtained by subsequent reclassification of the dimer class into three subclasses using the same unsupervised maximum likelihood approach. To speed up these calculations all particles were down-scaled inside the maximum likelihood program to 40 × 40 × 40 voxels (corresponding to a voxel size of 0.84 nm).

CTF correction
Projection images were aligned (Nickell et al., 2005) and Periodogram averaging (Fernández et al., 1997) was extended over these aligned images resulting in a mean power spectrum for each tilt series (Fernández et al., 2006). The mean power spectrum was filtered (van Heel et al., 2008) to improve the visibility of the Thon rings. Then, the mean defocus was calculated as previously (Scheres et al., 2009). A smaller spread of ribosome dimer orientations could also be obtained by subsequent reclassification of the dimer class into three subclasses using the same unsupervised maximum likelihood approach. To speed up these calculations all particles were down-scaled inside the maximum likelihood program to 40 × 40 × 40 voxels (corresponding to a voxel size of 0.84 nm).

Fitting of high resolution structures
Fitting was performed in a quantitative manner using Chimera (Petterson et al., 2004). Docked crystal structures were derived from Protein Data Bank (PDB), entries 2AW7 and 2AWB (Schuricht et al., 2003), or 1VOQ and 1VOR (Vla-Sanjurjo et al., 2004). For 3D visualization, the programs Chimera (Petterson et al., 2004) and 3ds max (Discreet) were used.

Accession numbers
The 3D density map of the 100S ribosome in conformation H has been deposited in the Electron Microscopy Data Bank with accession code EMD-1750.

Online supplemental material
Fig. S1 shows the orientation conventions used in this study. Fig. S2 is the complete analysis of spatial relationship of in situ identified ribosomes. Fig. S3 shows the resolution improvements gained by CTF correction applied to in vitro data. Fig. S4 shows subsequent unsupervised classification of previously identified ribosome dimers. Table S1 lists the identified protein in crude ribosomal fractions from starved Escherichia coli cells. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.201005007/DC1.

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