Mechanism of Protein Biosynthesis

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INTRODUCTION

The amino acid sequence of a particular protein is specified by the sequence of nucleotides in a particular segment of the deoxyribonucleic acid (DNA). The process of protein synthesis consists of two stages. First, the DNA is transcribed into a ribonucleic acid (RNA) intermediate, messenger RNA (mRNA), which has a ribonucleotide sequence complementary to that of the deoxyribonucleotide sequence of one of the strands of the DNA serving as template (transcription) (120). The mRNA becomes attached to cytoplasmic ribonucleoprotein particles (ribosomes) which are the sites of protein synthesis, and there it determines the order of linkage of amino acids into a specific protein (translation) (17, 243, 291). The mRNA is translated in the 5' to 3' direction (291).

The synthesis of a protein is initiated at the amino-terminal amino acid and proceeds towards the carboxy-terminal amino acid (17, 32a, 84a, 243, 291). During translation, a group of three adjacent nucleotides in the mRNA (codon) specifies which amino acid is to be linked to the growing peptide chain. It has been established which codons specify each of the 20 amino acids (74). (This is the genetic code.) It appears that the sequence of amino acids in a polypeptide chain contains all of the information required for generating the three-dimensional structure of the native protein molecule (chain folding) (13). The topic of this review is restricted to certain aspects of the mechanism of translation, mainly, although not exclusively, as elucidated in microorganisms. The regulation of protein synthesis (99) is not discussed. A collection of significant investigations on mammalian protein synthesis was presented in a volume dedicated to the memory of R. Schweet (14). Similar studies in plant systems have been described recently (5).

Abbreviations

Shorthand writing of oligonucleotides and polynucleotides and abbreviations for nucleotides, amino-acid residues, etc., are as recommended in J. Biol. Chem. 241:527 (1966).

In addition to those identified in the text, abbreviations are used as follows: RNA capable of accepting, for example, glycine, tRNA Gly; aminoacyl-tRNA, AA-tRNA (e.g., Gly-tRNA); mischarged tRNA species, for example, Ala-tRNA Cys; different tRNA species capable of accepting the same amino acid, isoaccepting tRNAs; N-acetyl AA-tRNA, acAA-tRNA (e.g., acPhe-tRNA); phe-phe-tRNA, diphe-tRNA; phe-phe-phe-tRNA, triphe-tRNA; aminoacyl oligonucleotides derived from AA-tRNA, for example, CpA-Gly or CACCA-acLeu; AA-tRNA synthetase aminoacyladenylate complex, E-AA-AMP; mRNA which is translated into more that one polypeptide, polygenic mRNA; polynucleotides with random sequence (e.g., a polymer containing adenylate, uridylate, and guanylate units), poly (A, U, G). Trinucleotide codons are shown by base initials (e.g., ApUpG, AUG).

Cell-free Protein Synthesizing Systems

In vitro systems have been a major tool for examining the mechanism of protein biosynthesis. They can be prepared (277) by disintegrating cells in aqueous media, removing unbroken cells and cell debris by low-speed centrifugation and small molecules by dialysis. To observe protein synthesis with such extracts, one requires the addition of adenosine triphosphate (ATP), guanosine triphosphate (GTP), an ATP-generating system, proper ions (Mg++ and either K+ or NH4+), sulfhydryl compounds (which were found to stabilize the system), and amino acids (some of which are usually radioactively labeled). In such a system, mRNA can be translated into protein. The translation is assayed by following the incorporation of labeled amino acids into protein. The messenger may be present in the extract (endogenous messenger), or it may be added (exogenous messenger). (In the latter case, the endogenous messenger is usually inactivated by incubating the extract before the amino acid incorporation experiment to provide time for the nucleases in the extract to degrade the endogenous mRNA.) The exogenous messenger can be either a natural or a synthetic polynucleotide. The use of synthetic polynucleotides of known composition or sequence was of utmost significance in deciphering the genetic code (214, 279, 280).

The cell extract can be further fractionated by centrifugation at high speed. The resulting supernatant fraction contains the following compo-
ments of the protein synthesizing machinery: tRNA (about 40 species), AA-tRNA synthetases (at least 20 species), and proteins involved in the elongation and termination of the peptide chain (at least 5 species). The resulting pellet contains: ribosomes (built from at least three kinds of ribosomal RNA and about 50 different kinds of ribosomal protein) and proteins required for peptide chain initiation (at least 3 species). The initiation factors can be removed from the ribosomes by washing with a buffer of high ionic strength. At this time more than 120 different macromolecules are known to be involved in the process of translation.

AA-tRNA SYNTHETASES

In every organism in which this was tested, there exist at least 20 AA-tRNA synthetases which link the correct amino acid presumably to the 3'-hydroxyl (246, 356) of the terminal adenosine of a specific tRNA molecule (see section on tRNA). The formation of AA-tRNA catalyzed by the AA-tRNA synthetase is a two-step reaction involving activation and transfer. The product of the activation step is the enzyme-bound amino- pyrophosphate (PP\(_\text{I}\)) the enzyme catalyzes the breakdown of the complex to ATP and amino acid. The incorporation of \(^{32}\text{P}\) into ATP is commonly used to estimate the formation of E-AA-AMP (ATP-PP\(_\text{I}\), exchange). Another assay is the reaction of E-AA-AMP with hydroxylamine to form the hydroxamate of the amino acid and AMP (see 307). In the transfer step, the activated amino acid is transferred onto the tRNA (a transacylation) to form AA-tRNA, the production of which can be measured directly.

The specificity of AA-tRNA synthetases, a prerequisite for faithful translation of the genetic message, must be very high (223, 290, 307) and is exercised at the level of amino acid activation as well as in the transfer step. The specificity in the latter step is higher than in the former; i.e., besides activating their cognate amino acids, Ile-tRNA synthetase activates valine and Val-tRNA synthetase activates threonine (21, 29, 157). These "wrong" amino acids are not then transferred to the tRNA, however. Certain amino acid analogues, however, do get charged onto tRNA (see 52, 274) and are subsequently incorporated into protein.

Although all of these enzymes perform the same function, there is no selective pressure to ensure that all of these molecules be very similar. Each aminoacyl-tRNA synthetase charges one or very few tRNA species. Consequently, mutations that change the mode of recognition between the enzyme and its substrates might be tolerated by the organism. Thus, the mode of recognition between the particular AA-tRNA synthetases and their substrates need not be the same, and a range of variation in physical and other characteristics of AA-tRNA synthetases does exist.

Since many aspects of AA-tRNA synthetases and amino acid activation have been discussed in

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Organism</th>
<th>Mol wt (× 10(^3))</th>
<th>((S_{20, w}))</th>
<th>Reference</th>
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<tr>
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<td>Yeast</td>
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<td>254</td>
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<td>Yeast</td>
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<tr>
<td>Lysine</td>
<td><em>E. coli</em></td>
<td>Yeast</td>
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<tr>
<td>Lysine</td>
<td><em>E. coli</em></td>
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<td>362</td>
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</tr>
<tr>
<td>Methionine</td>
<td><em>E. coli</em></td>
<td>Yeast</td>
<td>212</td>
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</tr>
<tr>
<td>Methionine</td>
<td><em>E. coli</em></td>
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<td>47</td>
<td></td>
</tr>
<tr>
<td>Phenylalanine</td>
<td><em>E. coli</em></td>
<td>Yeast</td>
<td>364</td>
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<td>Yeast</td>
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<td></td>
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<tr>
<td>Proline</td>
<td><em>E. coli</em></td>
<td>Yeast</td>
<td>247</td>
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<td>Serine</td>
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<td><em>E. coli</em></td>
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<td><em>E. coli</em></td>
<td>Yeast</td>
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<tr>
<td>Threonine</td>
<td>Rat liver</td>
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</tr>
<tr>
<td>Tyrosine</td>
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<tr>
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</tr>
<tr>
<td>Valine</td>
<td>Yeast</td>
<td></td>
<td>201</td>
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more detail previously (290, 307), only a few selected points will be presented here.

**Isolation and Properties of AA-tRNA Synthetases**

To date, a large number of AA-tRNA synthetases from various sources have been purified (Table 1). Most of the known enzymes have a molecular weight of around 100,000 (see Table 1 and reference 269). However, Phe-tRNA synthetases from yeast (234) and *Escherichia coli* (364), as well as Ala-tRNA (269) and Met-tRNA (212) synthetases of *E. coli*, have a molecular weight of about 173,000. The amino acid composition of a number of AA-tRNA synthetases has been determined, but there is much less information about their physical structure. In a few cases, AA-tRNA synthetases have been dissociated by such reagents as urea or guanidinium chloride into subunits of molecular weight about 50,000. It is not known whether the subunits formed are identical or different. For Pro-tRNA synthetase, no enzymatic activity was found in subunits of molecular weight 47,000 (210). The molecular weight of Met-tRNA synthetase purified from *E. coli* K was reported to be 173,000 (212). On incubating this enzyme with a factor isolated from the 100,000-g pellet fraction of the crude extract, it is depolymerized into enzymatically active synthetase molecules of molecular weight 54,000. Treatment of the high-molecular-weight enzyme with dissociating agents (e.g., 8 M urea) results in subunits of molecular weight 43,000 whose enzymatic activity has not yet been determined (65). Met-tRNA synthetase was also isolated (by a method different from the one used for the *E. coli* K enzyme) from another strain of *E. coli* [MRE 244 (47)]. The molecular weight of this enzyme was reported as 96,000.

The kinetic parameters of the AA-tRNA synthetases, in the cases where they have been determined, seem to be very similar. Measured in the overall reaction (aminoacylation of tRNA) the $K_m$ for the amino acid is between $10^{-4}$ and $10^{-3}$ M; for ATP, around $10^{-6}$ M; and for tRNA, between $10^{-7}$ and $10^{-6}$ M. The $K_m$ for ATP and amino acid in the activation step depends upon the nature of the assay and is different for the same AA-tRNA synthetase when measured by ATP-PP$_1$ exchange or by hydroxamate formation (see below). The various AA-tRNA synthetases have different optimal requirements for ATP, Mg$^{++}$, and other ions.

The kinetic methods in current use are still insufficiently precise and too slow to allow detailed unraveling of the exact sequence of reaction steps of amino acid activation (leading to E-AA-AMP formation) and tRNA acylation. In two cases, however, a complex of ATP and the AA-tRNA synthetase has been isolated. This might indicate that ATP is bound to the enzyme before the amino acid (4, 328).

Some lines of evidence suggest that the site for amino acid activation is different from the site for amino acid transfer (64). When *E. coli* Met-tRNA synthetase was treated with parahydroxymercuri benzoate (pHMB) in the presence of methionyladenylate, a structural analogue of methionyladenylate, the enzyme retained the ability to activate methionine [as tested by ATP-PP$_1$ exchange], but could no longer catalyze the formation of Met-tRNA. The reaction with pHMB did not alter the molecular weight of the enzyme. This suggests that the sites for the two reaction steps are different. "Cold" treatment of *E. coli* Pro-tRNA synthetase was reported to impair the transfer step to a much larger extent than the activation step (300). Whether this is due to dissociation of the enzyme into subunits at low temperatures remains to be determined (210).

**Reaction Mechanism**

In the activation step the AA-tRNA synthetase catalyzes the formation of the aminoacyladenylate, which remains bound to the enzyme and does not accumulate as a free intermediate. The activation reaction can be followed readily by ATP-PP$_1$ exchange for all synthetases, but the product aminoacyladenylate is not always detected in the alternate assay (hydroxamate formation). This was demonstrated in a comparative study of 14 *E. coli* AA-tRNA synthetases (157). The initial rates of the overall reaction (the formation of AA-tRNA) and of the activation step (the formation of hydroxylamine-sensitive aminoacyladenylate) were measured. For some enzymes, the same rate was observed by each assay, but for others, no hydroxamate formation was detectable. Thr-tRNA synthetase, for instance, forms threonyladenylate (as shown by ATP-PP$_1$ exchange as well as by isolation of the E-Thr-AMP complex), but this does not react with hydroxylamine under standard conditions (156). After the addition of tRNA, threonylhydroxamate is formed by a nonenzymatic reaction of Thr-tRNA with hydroxylamine. It was suggested that the threonyladenylate is buried inside the enzyme molecule, inaccessible to hydroxylamine. Similar lack of hydroxamate formation was shown for Thr-tRNA synthetase of calf liver (219).

Although the formation of E-AA-AMP requires in most cases only the presence of amino acid, ATP, and Mg$^{++}$, a few cases have been found in which the presence of tRNA is required for amino acid activation. Glu-tRNA synthetase from *E. coli*, pork liver, and yeast (209, 317) catalyzes glutamyladenylate formation only at
very high glutamate concentrations. However, in the presence of tRNA, very low glutamate concentrations are sufficient for synthesis. The tRNA\textsuperscript{Gln} is strictly required under any conditions for the formation of glutaminyladenylate by its cognate enzyme in the same three organisms. The same is true for E. coli Arg-tRNA synthetase (248) and rat liver Gly-tRNA synthetase (105). In the latter case, however, the activation was measured only by hydroxamate formation, and thus the conclusion may be invalidated by the limitations of the hydroxamate method discussed above. It was reported that tRNA activates arginyl-adenylate formation catalyzed by Arg-tRNA synthetase (252). It is possible that the apparent need for tRNA in amino acid activation in the case of certain synthetases, but not in that of others, reflects that the order of binding of the substrates (ATP, amino acid, tRNA) to the synthetases may not be the same for all enzymes.

The E-A-A-AMP complex has been isolated by gel filtration for a variety of enzymes (4, 6, 33, 136, 200, 289, 397). The isolated complex can be used in the elucidation of the reaction mechanism of the transfer step. Differences between enzymes are apparent in the requirement for inclusion of divalent metal ions in the reaction mixture in which the transfer of the amino acid from the complex onto the tRNA is tested. The transfer proceeds without metal ions in the case of E. coli Ile-tRNA (289) and Lys-tRNA (397) synthetase as well as yeast Val-tRNA (200) synthetase. The transfer requires Mg\textsuperscript{++} ions in the case of Thr-tRNA synthetase from rat liver (4) and from E. coli (156), Ile-tRNA synthetase from Bacillus stearothermophilus (136), and Ser-tRNA synthetase from yeast (33). Some other divalent metal ions may substitute for Mg\textsuperscript{++} (156).

**Complexes Between AA-tRNA Synthetases and tRNA**

Stable complexes between tRNA and its cognate AA-tRNA synthetase have been obtained with yeast Val-tRNA synthetase (199, 200) and Leu-tRNA synthetase (341), as well as with Ile- and Tyr-tRNA synthetase from E. coli (418) and Arg- and Gly-tRNA synthetase from B. stearothermophilus (294). The tRNA—AA-tRNA synthetase complexes, isolated by gel filtration on Sephadex G-100, by sucrose density gradient centrifugation, and by electrophoresis, have been shown to be enzymatically active. If the stable complex is isolated on a membrane filter (Millipore Corp., Bedford, Mass.), however, the enzyme is completely inactivated (418). The complex formation is usually specific for the tRNA and its cognate AA-tRNA synthetase. Lack of specificity has been observed (199), however, at low salt concentrations. Complex formation between synthetases and tRNA from heterologous systems also occurs (294).

Whether the acceptor end of the tRNA molecule is involved in this complex formation remains controversial (200, 293, 294). In some cases, periodate-oxidized tRNA will not bind to or inhibit AA-tRNA synthetase, whereas the opposite is true in other cases. These findings suggest that the process of recognition between tRNA and its cognate AA-tRNA synthetase may vary from case to case.

**Genetics of Synthetases**

Mutants for a number of AA-tRNA synthetases have been isolated from or found in E. coli, Salmonella typhimurium, and yeast (see Table 2). The genetic loci of the E. coli AA-tRNA synthetases (as far as they have been determined) are scattered all over the chromosome. The temperature-sensitive synthetase mutants display little activity in in vitro tests even at low temperature, and some possess a decreased affinity for amino acid, ATP, or both. In some cases, they can be protected against heat denaturation by the presence of amino acid, ATP, or Mg\textsuperscript{++}. Most of the present data on E. coli are consistent with the existence of only one AA-tRNA synthetase for each amino acid. It remains to be seen whether reports of several AA-tRNA synthetases for the same amino acid in E. coli (66, 420) could possibly be attributed to aggregates or to tRNA—AA-tRNA synthetase complexes (341). In higher organisms, the occurrence of multiple synthetases (22, 164, 393) is partly accounted for by the recent discovery (24, 48) of different AA-tRNA synthetases (specific for the same amino acid) in the mitochondria and the cytoplasm of the same cell. It has been shown that a mitochondrial Leu-tRNA synthetase is specified by a nuclear gene (137).

**TRANSFER RNA**

**Sequence of tRNA**

Since the elucidation of the first tRNA sequence (160), great progress in tRNA fractionation techniques (126, 127) and sequencing methods (334) stimulated the pace of tRNA sequence analysis. At present, the primary sequences of 17 tRNA species from bakers’ (90, 160, 231, 273, 312) and brewers’ (423) yeast, E. coli K-12 (76, 89, 129) and B (M. Uziel, unpublished data; U. L. Raj-Bhandary, unpublished data), Torulopsis utilis (379, 380), rat liver (360), and wheat germ (90) have been established. The chain length of the
MECHANISM OF PROTEIN BIOSYNTHESIS

Table 2. AA-tRNA synthetase mutants

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Organism</th>
<th>Genetic location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alanine</td>
<td>Escherichia coli</td>
<td>Between purC and thy</td>
<td>416</td>
</tr>
<tr>
<td>Arginine</td>
<td>E. coli</td>
<td>between aroD and his</td>
<td>158</td>
</tr>
<tr>
<td>Glycine</td>
<td>E. coli</td>
<td>Near xyl</td>
<td>35</td>
</tr>
<tr>
<td>Histidine</td>
<td>E. coli</td>
<td></td>
<td>268</td>
</tr>
<tr>
<td>Histidine</td>
<td>Salmonella</td>
<td>Near strB</td>
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</tr>
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<td>374</td>
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<td>Yeast</td>
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</tr>
<tr>
<td>Phenylalanine</td>
<td>E. coli</td>
<td>At min 33a</td>
<td>92, 104, 173</td>
</tr>
<tr>
<td>Serine</td>
<td>E. coli</td>
<td>Between min 17 and 19a</td>
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</tr>
<tr>
<td>Tryptophan</td>
<td>E. coli</td>
<td>Between str and malA</td>
<td>88</td>
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<tr>
<td>Valine</td>
<td>E. coli</td>
<td>At min 87a</td>
<td>92, 173, 415</td>
</tr>
</tbody>
</table>

* On the Taylor map (384).

Fig. 1. (a) Nucleotide sequence of a yeast tRNAAla (84). (b) Nucleotide sequence of an E. coli tRNAfMet (94). Both sequences are shown in a cloverleaf-type arrangement. Minor nucleosides: Gm1, N7-methylguanosine; H, dihydrouridine; Gm2, N7-dimethylguanosine; m1, methylinosine; ψ, pseudouridine; U* (Fig. 1a), a mixture of U and H; U* (Fig. 1b), nature of base still in doubt; T, ribothymidine; Cm, 2′O-methylcytidine.

Known tRNA molecules vary between 75 and 85 nucleotides, and their content of minor bases (143) between 10 and 20%. The primary sequences of all these tRNAs can be arranged (satisfying base-pairing requirements) in a cloverleaf model (230; Fig. 1). The additional bases of the larger tRNA are taken up in the minor loop. With the exception of the anticodon and the CCA-acceptor end, no structural features can yet be assigned to the other functions of the tRNA molecule. However, tRNAfMet exhibits unusual base pairing near the 5′ and 3′ end of the molecule. In all other tRNAs of known sequence (e.g., in tRNAAla from yeast, whose base sequence is shown in Fig. 1a), base pairing starts at base number 5, measured from the amino acid acceptor end, whereas in tRNAfMet (Fig. 1b) base pairing starts at base number 6 (89). Many attempts to determine the secondary (85, 275) and tertiary (202) structure of tRNA have been...
made (114), so far providing no really convincing evidence for any model. Recent progress in the crystallization of tRNA from *E. coli* and yeast (69, 78, 113, 146, 180) has encouraged the hope that the tertiary structure of tRNA will be determined by X-ray crystallography. Crystallization of the complex of tRNA and its cognate AA-tRNA synthetase may prove even more illuminating.

**Genetics of tRNA**

So far tRNA has been accessible for genetic studies only in very rare cases. Nonsense mutations of the amber and ochre type are known to cause premature peptide chain termination (117), and their suppression in *E. coli* has been shown to be due in some cases to a suppressor tRNA (59, 97, 129, 130, 352, 411). The anticodons of the tyrosine suppressor tRNA and of the corresponding tRNA\(^{\text{**}}\) species from a strain not carrying the suppressor mutation differ in a single nucleotide (129). This provides evidence for the assumption that the suppressor mutation occurred in the structural gene for the tRNA. The genetic loci for the suppressor tRNA are distributed all over the chromosome. Work on the regulation of histidine biosynthesis in *S. typhimurium* has revealed a class of mutants believed to be mutants in tRNA\(^{\text{bis}}\) (347).

**Recognition of tRNA by the AA-tRNA Synthetase**

The question of the specific recognition site on the tRNA for its cognate AA-tRNA synthetase is the oldest and still foremost open question in tRNA research. Whereas some earlier experiments were taken to support the view that the anticodon is a specific recognition site for the AA-tRNA synthetase (254), there is mounting evidence that this may not be so, at least not for all tRNA. The *E. coli* tyrosine amber suppressor tRNA, which differs by a single base in the anticodon from its "parental" tRNA\(^{\text{**}}\) (129), is active in vivo and in vitro suppression (119). This shows that the tRNA with a changed anticodon is still recognized by the AA-tRNA synthetase. Chemical modification of pure tRNA species with known sequences also supports this conclusion. *Torulopsis* tRNA\(^{\text{**}}\) (150), cyanoethylated only in the pseudouridine residue of the anticodon, could be charged by purified Tyr-tRNA synthetase to the same extent as unmodified tRNA, albeit at a much slower rate. Similar results were obtained in experiments with yeast tRNA\(^{\text{bis}}\) (419). Treatment of a tRNA\(^{\text{bis}}\) with nitrous acid resulted in a change in its coding specificity (60). The tRNA (modified presumably in the anticodon) could be charged by the Gly-tRNA synthetase, although at a slower rate (61).

Modification of a base next to the anticodon [i.e., the isopentenyladenosine (ipA) residue in tRNA\(^{\text{**}}\) (106) and tRNA\(^{\text{**}}\) (119)], or the elimination of a base (386), do not impair the ability of the tRNA to be charged. The tRNA partially or fully lost their ability, however, to participate in protein synthesis, probably because of a different conformation of the anticodon loop. Experiments with isoaccepting *E. coli* tRNA\(^{\text{**}}\) species also support the view that the anticodon need not be the specific recognition site for the AA-tRNA synthetase (372). Two tRNA\(^{\text{**}}\) species specified by entirely unrelated codons (UCA and AGU) could be charged to the same extent and at the same rate by a purified *E. coli* Ser-tRNA synthetase preparation. The two tRNA species competed for the Ser-tRNA synthetase, indicating that they were recognized by the same enzyme. In a different kind of experiment, pure yeast tRNA\(^{\text{Val}}\) was split by T1-ribonuclease next to I in the anticodon sequence. The separated half-molecules did not possess acceptor activity. The mixture of both halves, however, accepted almost the theoretical amount of valine despite the break in the polynucleotide chain (25). This shows that the anticodon does not need to be intact for recognition by the AA-tRNA synthetase.

According to a recent hypothesis (345) based on studies of ultraviolet-inactivation of tRNA\(^{\text{Ala}}\), the three base pairs closest to the acceptor end of a tRNA molecule represent the specific recognition site for the AA-tRNA synthetase. Two sets of experiments, however, cast some doubt on the general validity of this hypothesis. Rat liver tRNA\(^{\text{Ser}}\) can be charged by yeast Ser-tRNA synthetase as well as by the homologous enzyme, although the nucleotide sequences in the presumed recognition site differ in two out of three base pairs in rat liver and yeast tRNA\(^{\text{Ser}}\) (360). Likewise, yeast tRNA\(^{\text{Met}}\) with a sequence different from the corresponding *E. coli* species can be charged by the *E. coli* Met-tRNA synthetase (313). However, in both cases, tRNA was charged by heterologous enzymes and, therefore, these results may not serve as a firm basis for invalidating the above hypothesis. The large degree of homology in the structures of the various tRNA makes it difficult to recognize a specific contiguous nucleotide sequence in an identical position in all tRNA as recognition site for the AA-tRNA synthetase. The process may involve the recognition of features of tertiary structure, as has been suggested (77).

**Minor and Redundant tRNA Species**

*E. coli* tRNA can be separated into a large number of distinct fractions by chromatographic
techniques (264, 408). Artifacts of preparation and chromatography resulting in tRNA aggregates (222, 354, 422) and in inactive (118, 217) and partially modified tRNA species may account for some of the fractions. However, there is cause to believe that many fractions are distinct minor tRNA species. In a few cases, these have been shown to be redundant tRNA (multiple iso-accepting tRNA specific for the same codon) (353, 354). The existence of redundant tRNA may explain certain mechanisms of nonsense or missense suppression (129, 139). At least two species of E. coli tRNA^Tyr^ have been shown to recognize the same codons. A mutation in one of the tRNA^Tyr^ genes resulting in a change in the anticodon of a tRNA^Tyr^ has been shown to be the origin of the tyrosine suppressor tRNA (129). This tRNA no longer recognizes the normal tyrosine codons, but reads an amber triplet as though it were a tyrosine codon. The remaining tRNA^Tyr^ species (not affected by this mutation) are sufficient for supporting normal protein synthesis. Observations on the number of different tRNA species are valid only in haploid organisms (having only one chromosome per cell), since mutations in one of duplicate tRNA genes could lead to redundant tRNA.

The composition of the tRNA population may vary in cells from different stages of growth (187; J. Bartz and D. Soll, unpublished data) and in cells grown in different conditions (86, 198). This poses the fundamental questions of how tRNA synthesis is regulated and why an organism maintains the production of minor redundant tRNA. It is possible that the latter species are used for yet unknown functions of tRNA in regulating and maintaining cell growth.

**Virus Infection and tRNA**

The changes in tRNA after infection of E. coli B with T2 or T4 phage have been studied extensively (370). Alterations in tRNA depend on protein synthesis; they are not observed if chloramphenicol is added prior to phage infection. The changes after infection are displayed in the same fashion whether the tRNA is charged with AA-tRNA synthetases derived from infected or uninfected cells, and they can be divided into two classes: inactivation of host-specific tRNA and appearance of phage-coded tRNA.

**Inactivation of host tRNA.** A change in the Leu-tRNA^Leu^ pattern on Methylated Albumin-kieselguhr (MAK) chromatography has been shown after T2 infection (172, 370). More recent studies involving fractionation of Leu-tRNA^Leu^ by reverse phase chromatography provide evidence for the selective inactivation of the major tRNA^Leu^ species (399, 400) and may support the notion (400) that this is due to the action of a phage-induced nuclease specific for this species. Concomitant with the inactivation of the major tRNA^Leu^ is the appearance of new, possibly phage-coded, tRNA^Leu^ species, as revealed by reverse phase chromatography (170, 172). Binding studies with fractions of Leu-tRNA^Leu^ from infected and uninfected cells were not completely successful in elucidating the coding response of the various tRNA^Leu^ species (171).

**Phage-coded tRNA.** The studies of cysteine-dependent thiolation of tRNA (163) provided another tool for testing tRNA after phage infection. In uninfected and phage-infected cells grown on ^35S^-sodium sulfate, all sulfur-containing RNA proved to be 4S RNA, the elution profiles of which on MAK columns were different for tRNA from infected and uninfected cells (163). The material of the major new peak from infected cells does not hybridize with E. coli DNA, but it hybridizes with T4 DNA; T4 mRNA and E. coli tRNA do not compete in this reaction (407). Using the elegant technique of hybridizing charged tRNA at low temperature, it was shown that at least one species of tRNA^Leu^ and of tRNA^Pro^ was coded by T2 phage (407).

Only sulfur-containing tRNA species can be detected by the above method. The failure to observe gross tRNA changes in cells infected with T-odd, MS2, or φX 174 phages, therefore, does not exclude the possibility that tRNA species are coded by these phages.

Herpes simplex virus was shown to specify at least one species of tRNA^*A^* (367, 368). The multiplication of the oncogenic BSV virus was reported to be associated with the appearance of virus-specific tRNA (391).

**Cytokinins and tRNA**

The cytokinins are substances which promote cell division, growth, and organ formation in plants. Their activity is usually measured by the increase caused in the cell mass of tobacco stem (151). Of all the cellular components, tRNA is uniquely associated with cytokinin activity. Such activity was found in the tRNA of bacteria, plants, and mammals.

Since the discovery of ipA, a very potent cytokinin, as a constituent of yeast tRNA (31, 145), many examples of cytokin-in-active nucleotides in crude and purified tRNA preparations have been reported (119, 144, 147, 231, 324, 348, 360, 379, 423). For instance, the derivative of ipA, N^4^-[cis-4-hydroxy-3-methyl-but-2-enyl] adenosine, occurs in the tRNA of plant tissues (144) and its 2-meth-
amino acid. Transfer Ala-tRNA\(^{\text{Ala}}\), Thr-tRNA in Micrococcus 242), of tapeptide for strains, in material cell walls (107, 185). It is interesting to note that the cytokinin-active E. coli tRNA species all recognize codons beginning with U. In the cytokinin-active tRNA of known sequence, ipA or its methylthio derivative is located adjacent to the anticodon (119, 231, 360, 379, 423; M. Uziel, unpublished data, and U. L. RajBhandary, unpublished data). The participation of the ipA residue in maintaining the fidelity of translation and the tertiary structure of the tRNA is evident in the following experiments. Treatment of tRNA\(^{\text{Ber}}\) with iodine leads to a tRNA with a modified ipA residue (106). The modified tRNA showed decreased binding to ribosomes in the presence of the appropriate mRNA, but retained the ability to be charged by its cognate AA-tRNA synthetase. E. coli suppressor tRNA\(^{\text{Ary}}\) was obtained in several forms which differ in the base adjacent to the 3′ nucleotide of the anticodon. The tRNA containing A or ipA in this position were much less active in vitro suppression than was the tRNA with 2-methylthio-ipA (119). Whether these effects on coding properties play a role in the mechanism of action of the cytokinins remains to be determined.

Treatment of tRNA with KMnO\(_4\) converts ipA residues to A residues; tRNA treated with KMnO\(_4\) was added to rat liver or yeast extract supplemented with labeled mevalonate or isopentenylpyrophosphate. It was established that in the extract isopentenyl side chains became linked to A residues of the treated tRNA. This linkage is catalyzed by an enzyme which is specific for certain A residues in selected tRNA molecules (107, 185).

**Cell Wall Synthesis and tRNA**

A novel role for tRNA has recently been discovered: it participates in the synthesis of bacterial cell walls and aminoacylphosphatidylglycerols, compounds found in certain bacteria. In vitro experiments with four different bacterial strains, a strict requirement has been shown for tRNA in the biosynthesis of the pentapeptide bridges linking the peptidoglycan strands of bacterial cell walls (49, 242, 308, 322, 323). Gly-tRNA in Staphylococcus aureus (49, 242), Thr-tRNA in Micrococcus roseus (323), Ser- and Gly-tRNA in S. epidermidis (308), and Ala-tRNA in Arthrobacter crystallopoietes (322) transfer their respective amino acids into the bridge. This reaction is catalyzed by a particulate enzyme fraction. The process is specific for the amino acid. Heterologous tRNA can replace the homologous tRNA in certain cases (242, 308, 322, 323). The substrate specificity of the enzyme for the tRNA was demonstrated in the following experiment: Ala-tRNA\(^{\text{Cys}}\) [prepared by desulfurization with Raney nickel from Cys-tRNA\(^{\text{Cys}}\) (67)] did not substitute for Ala-tRNA\(^{\text{A1a}}\) in the bridge peptide formation as catalyzed by the enzyme fraction from A. crystallopoietes (322). The role of tRNA was further clarified by fractionation of crude tRNA. Gly-tRNA, Ser-tRNA, and Thr-tRNA obtained from S. aureus, S. epidermidis, and M. roseus, respectively, were fractionated into a number of isoaccepting tRNA species with different coding properties. All these tRNA species participated in in vitro peptide bridge formation. Some of them, however, did not bind to ribosomes in the presence of the corresponding trinucleotide codons and did not support in vitro protein synthesis directed by synthetic and natural messengers. Thus, it seems unlikely that the anticodon is involved in the tRNA specificity.

Studies with a purified Gly-tRNA synthetase from S. aureus have indicated that the same enzyme charges tRNA for protein synthesis and for peptidoglycan synthesis (283). The mechanism of tRNA participation in the peptide bridge formation is not clear. The process is distinctly different from protein biosynthesis since it proceeds apparently without ribosomes and in the presence of antibiotics like puromycin or chloramphenicol, which are known to block protein synthesis. The synthesis of lysylphosphatidylglycerol in S. aureus requires Lys-tRNA, and also proceeds with heterologous tRNA (215). The high specificity of the aminoacylphosphatidylglycerol synthetases for tRNA and also for the amino acid has been shown in experiments with a series of chemically or enzymatically produced “mischarged” tRNA species (134, 276) which all possessed acceptor activity after modification. Thus, in the synthesis of alanlyphosphatidylglycerol in extracts of Clostridium welchii, N-acetyl-Ala-tRNA\(^{\text{A1a}}\), lactyl-tRNA\(^{\text{A1a}}\), Ala-tRNA\(^{\text{Cys}}\), Cys-tRNA\(^{\text{Cys}}\), and Phe-tRNA\(^{\text{A1a}}\) could not substitute for Ala-tRNA\(^{\text{A1a}}\) (134).

**Differentiated Cells and tRNA**

Transfer RNA has been found in mitochondria isolated from yeast (412), Neurospora (23), Tetrahymena (373), and rat liver (48, 216). Differences have been shown in chromatographic properties between isoaccepting tRNA of mitochondrial and cytoplasmic origin from the same organism. It remains to be seen whether mitochondrial tRNA is transcribed from nuclear or from mitochondrial DNA (373).

Differences have also been found between the
chromatographic patterns of the tRNA extracted from various differentiated cells (208, 413), malignant cells (382), and cells involved in specific antibody response (414).

Other tRNA Reactions

Several reactions are known which involve modification of the aminoacyl residue of AA-tRNA. One is the formylation of Met-tRNA$^f_{Met}$ to yield fMet-tRNA$^{Met}$ (237). Another reaction is the conversion of glutamic acid attached to tRNA to glutamine in B. megatherium (410). A still uncharacterized enzyme catalyzes the formation of Glu-tRNA$^{Gln}$, which is converted subsequently to Gln-tRNA$^{Gln}$ by a transamidase in the presence of an amide donor. The significance of this reaction is not known. The cyclization of the glutamine residue of E. coli Gln-tRNA$^{Gln}$ to pyrroloidine carboxylate-tRNA$^{Gln}$ by an enzyme from papaya latex has been reported recently (30). The enzyme displays no specificity for tRNA since it also cyclizes N-terminal Gln-residues of peptides.

RIBOSOMES

Ribosomes are large ribonucleoprotein particles on which the actual process of translation takes place. There are two functionally different subunits of E. coli ribosomes, the 30S and the 50S subunits. The 30S subunit consists of about 20 different proteins and one species of RNA (16S), whereas the 50S subunit contains about 30 different proteins (G. R. Craven and C. Kurland, unpublished data) and two species of RNA (5S and 23S). Heavy subunits of mammalian ribosomes have been reported to contain an additional RNA species (110, 304). The most dramatic progress in this field during the past 2 years has been the physical and chemical characterization of the components of E. coli ribosomes and the in vitro reconstitution of active ribosomes from separated nucleic acid and protein components. This discussion is restricted to the above subjects. Other aspects of the formation and structure of bacterial ribosomes have been summarized recently (298). The biosynthesis of ribosomes in animal cells has been discussed in a recent review (82).

Ribosomal Proteins of the 30S Subunit

Twenty-one protein components have been separated from the E. coli 30S subunits by column chromatography and by polyacrylamide gel electrophoresis (79, 109, 261, 389). Nineteen of these are different proteins since each of them has a unique amino acid composition and fingerprint pattern of its tryptic peptides. The molecular weights of the different ribosomal proteins vary from 5,000 to 63,000, although the exact molecular weight of each protein and the stoichiometry of these species in a 30S subunit is not yet agreed upon. The question of molecular weight is very important; if the molecular weights and stoichiometry reported by one group of investigators were correct, then the sum of the weights of individual proteins would be larger than the total amount of protein in a 30S subunit. The implication from these results would then be that there is more than one kind of ribosome (79).

The acrylamide gel electrophoretic patterns of the proteins from 30S subunits of E. coli strain K-12 and strain B differ in the position of a single band (205). The two proteins corresponding to these characteristic bands have similar molecular weights of about 20,000, but the proteins differ in at least 10 amino acid residues (32).

Studies comparing the ribosomal proteins of procaryotic and eucaryotic organisms are under way (68, 169, 363).

Ribosomal RNA

5S RNA. 5S RNA can be prepared by phenol extraction of whole cells (327) or from isolated ribosomes (122). With the exception of tRNA, it is the smallest RNA, having a chain length of 120 nucleotides and lacking minor bases. The nucleotide sequence of 5S RNA from E. coli (46) and from a human tumor line [KB (111)] has been established, and it is interesting to note that a part of the nucleotide sequence is duplicated in each of the two 5S RNA species. The sedimentation coefficient of 5S RNA varies from 4.4 to 4.7, depending upon salt and Mg$^{2+}$ concentration (36, 122). Several conformations have been suggested for this polynucleotide (18, 36, 46, 55). No function is known for the 5S RNA, although there is a recent report (181) according to which its presence stimulates the phase f2 RNA-directed protein synthesis in vitro.

16S and 23S RNA. Studies on the terminal sequences of 16S and 23S ribosomal RNA have been performed on RNA from a variety of organisms (230). A heterogeneity in the 3' terminal nucleotide of the 23S ribosomal RNA has been reported. Ribosomal RNA contain small amounts of methylated bases, and the sequences around these minor bases have been examined (108). The methylation occurs only at a small number of sites. The sequences in the neighborhood of methylated nucleotides occur twice in each 23S RNA molecule.
Reconstitution of Active Ribosomes from RNA and Protein

In solutions of high ionic strength, 30S and 50S ribosomal subunits dissociate into smaller ribonucleoprotein particles (core particles) and proteins. By combining these components in properly selected conditions, ribosomes active in vitro protein synthesis were reconstituted several years ago (287, 359). Recently, 23S core particles from the 30S subunit have been dissociated into free 16S RNA and proteins. The separated RNA and core proteins were mixed at 37°C, cooled to 4°C, and the additional protein fractions from the 30S subunit were added (390). The reconstituted particles had the same sedimentation coefficient as native 30S subunits, and when combined with 50S subunits were fully active in vitro protein synthesis directed by poly U or phage f2 RNA. No difference in the number or in the nature of the protein components was found between reconstituted and native 30S subunits. Proteins from 50S subunits could not substitute for those from 30S subunits in the reconstitution of functionally active 30S subunits. In similar reconstitution experiments with the 30S subunit proteins from E. coli, the intact 16S E. coli RNA could not be replaced by degraded E. coli ribosomal RNA, 16S yeast ribosomal RNA, or 18S rat liver ribosomal RNA. However, 16S RNA from either Azotobacter vinelandii or B. stearothermophilus did substitute for E. coli 16S RNA (288).

The availability of techniques for separating all the ribosomal proteins has opened the way for elucidating the function of the individual proteins. In reconstitution experiments with isolated proteins and RNA from streptomycin-resistant, streptomycin-dependent, and streptomycin-sensitive 30S subunits, a particular protein (of molecular weight 14,000) was shown to be the target of streptomycin action; 30S subunits were reconstituted from the 16S RNA and a mixture of proteins lacking the streptomycin target protein. To the incomplete particles obtained, streptomycin target protein was added, which was obtained from either streptomycin-resistant (299), streptomycin-sensitive (299), or streptomycin-dependent (C. Kurland, unpublished data) ribosomes. The behavior of the reconstituted 30S subunit toward streptomycin was determined by the origin of the streptomycin target protein used in this experiment.

PEPTIDE CHAIN INITIATION

Much of our knowledge about initiation has come from studies on E. coli and a few other microorganisms. The components known to be involved in this process include an initiator tRNA (fMet-tRNAf) responding to initiator codons, several initiation factors, ribosomal subunits, and GTP.

About 40% of the E. coli proteins have methionine as the N-terminal amino acid, although methionine constitutes only 2.5% of the total amino acid in proteins. Methionine, alanine, serine, and threonine together account for about 95% of the N-terminal amino acids in these proteins (398). Over 60% of the Met residues attached to E. coli tRNA have their α-amino group formylated. No other N-formylated AA-tRNA has been detected. The formylation of the α-amino group of methionine occurs after the amino acid has been esterified by tRNA; N-formylmethionine itself does not become linked to tRNA (239). The formyl donor is Nα-formyltetrahydrofolate (2, 84, 237). The formylating enzyme, Met-tRNA transformylase, has been purified from E. coli (84).

There are at least two classes of methionine-accepting tRNA species in E. coli: tRNAf and tRNAf*. Met-tRNAf can be formylated enzymatically, whereas Met-tRNAf* cannot (70, 71). The tRNAf* exhibits unusual base pairing near the 3' and 5' ends (89). This uniquely distinguishes it from all other tRNA of known sequence (cf. Sequence of tRNA).

Initiator of Peptide Chains: fMet-tRNA

The RNA of bacteriophage f2 and R17 can serve as mRNA and, as such, direct the synthesis of at least three virus-specific proteins in the cell-free amino acid-incorporating system from E. coli (59, 272). Each of these proteins formed in vitro have N-formylmethionine as the N-terminal amino acid (2, 221, 394, 402). This indicates that fMet-tRNA can serve as a peptide chain initiator for each of the proteins programmed by a polygenic mRNA.

The dependence of in vitro protein synthesis directed by f2 RNA on fMet-tRNA was demonstrated in the following way. To deplete E. coli of fMet-tRNA and the formyl donors (i.e., formyltetrahydrofolate) the synthesis of their precursor (tetrahydrofolate) was blocked by Trimethoprim, an inhibitor of dihydrofolate reductase (50). In the cell-free extract of Trimethoprim-treated E. coli cells, amino acid incorporation directed by f2 RNA strictly depends upon either added fMet-tRNA or formyltetrahydrofolate [which makes possible the formation of fMet-tRNA in the extract (96)]. This dependence is found only at low Mg++ concentration (4 to 8 mM). At high Mg++ concentration, the incorporation is only partially or not at all dependent on fMet-tRNA (96, 188).
The following result indicates that fMet-tRNA is the major, if not the only, peptide chain initiator in E. coli. In a cell-free extract of E. coli in which protein synthesis was directed by endogenous mRNA, one fMet residue was incorporated for approximately 150 amino acids, and formylmethionine was the only formyl-amino acid (56).

**Fate of the Formyl and the fMet Residues**

As stated earlier, the majority of E. coli proteins have methionine, alanine, serine, or threonine as the N-terminal amino acid. On the other hand, most, if not all, of the E. coli proteins are initiated by N-formylmethionine. This suggests that E. coli (and presumably other bacteria) have an enzyme or enzymes which remove the formyl and in certain cases also the Met residue from the N-terminal end of the peptide chain. Extracts from certain microorganisms [E. coli, B. stearothermophilus, and B. subtilis (1, 115, 378)] were found to contain enzymes cleaving fMet-peptides into formate and Met-peptides. A protein fraction from E. coli which contained such a peptide defomylase was found to liberate formate from proteins synthesized in vitro. The rate of hydrolysis of fMet-peptides by this protein fraction was greater than that of other formyl-peptides, acetyl-Met-alanine or N-formylmethionine. Such characteristics are those expected from an enzyme whose physiological function is to remove formyl residues from nascent protein (1). The fMet-phenylalanyl-tRNA is a substrate for the defomylase, whereas fMet-tRNA is not. This suggests that the defomylase may occur soon after the incorporation of the fMet residue into a fMet-AA-tRNA intermediate (220). The peptide defomylase of E. coli is very labile in vitro and is inhibited strongly by compounds with sulphydryl groups. The proteins synthesized in vitro retain their formyl residue presumably because the defomylase does not survive the procedures used in preparing and testing the cell-free extract (1).

Since the peptide defomylase removes only formyl residues, it is expected that other enzymes are responsible for removing the Met residues. Extracts from E. coli and B. subtilis contain an aminopeptidase capable of removing a Met residue from Met-puromycin (but not from fMet-puromycin), and from the N-terminal hexapeptide of f2 coat protein (but only after the formyl residue has been cleaved off by treatment with the defomylase). These observations indicate that if a fMet residue is removed from a nascent protein, this takes place in two steps: first, the formyl residue is cleaved off, and subsequently, the Met residue (378).

E. coli extracts can also cleave N-formylmethionine (409). This cleavage is believed to be due to acetylmethionine deacetylase action. In the extract of an E. coli mutant lacking acetylmetionine deacetylase, the rate of hydrolysis of N-formylmethionine was only 1% of that observed in the extract of wild-type E. coli (115).

The amino acid adjacent to fMet is not unique in the proteins isolated from an E. coli extract in which protein synthesis was directed by endogenous mRNA. Alanine, serine, and, to a smaller extent, other amino acids were found in the position adjacent to the N-terminal residue of the peptide chain (56).

It remains to be seen if the amino acid adjacent to the fMet residue determines whether the Met residue is removed by the aminopeptidase or if other factors (e.g., the secondary structure of the protein) are decisive.

**Coding Specificity and Functions of tRNA<sub>F</sub> and tRNA<sub>M</sub>**

One of the methods used in deciphering the code was based on the fact that particular ribonucleotides or ribonucleotides promote the binding of different AA-tRNA to ribosomes. This binding can be conveniently tested since free AA-tRNAs are not held on nitrocellulose membrane filters, whereas those whose binding to ribosomes is promoted by the proper codon are retained [the so called "binding assay" (278)]. The binding assay and the promotion of amino acid incorporation by mRNA of defined sequence were the techniques used in studies with cell-free systems on the coding specificities and functions of the two methionine-accepting tRNA species. It was concluded that, whereas fMet-tRNA serves as a source of N-terminal Met residues, Met-tRNA<sub>M</sub> provides Met residues for internal and C-terminal positions of the polypeptide chains (71, 124, 331). The codons specifying tRNA<sub>F</sub> are AUG and GUG; the codon specifying tRNA<sub>M</sub> is AUG (71, 124, 331, 371).

**Phasing Activity of Initiator Codons**

If an AUG codon is at or near the 5' end of a polynucleotide, it decreases the binding (of AA-tRNA to ribosomes) by the codons partially overlapping with the AUG sequence and increases the binding by the codons adjacent to the 3' side of AUG. For example, AUG(U)<sub>14</sub> stimulates the binding of Met- and Phe-tRNA, but not of Val-tRNA. (UUU codes for phenylalanine, GUU for valine.) In contrast, AUGG(U)<sub>14</sub> stimulates the binding of Met- and Val-tRNA, whereas the binding of Phe-tRNA is reduced to a low level. AUG thus seems to set the phase of reading. This phasing activity is maximal at low Mg<sup+</sup> concentration. At higher Mg<sup+</sup> concentration, this effect of the AUG
codon diminishes, and the selection of the reading frame is random (371, 385).

The in vitro translation of synthetic messengers not having an AUG codon at or near the 5' end apparently starts mostly at the second triplet (351). Messengers with AUG at the 5' end, however, are translated from the 5' end (361). Since neither AUG nor GUG is part of the sequence of the first 10 nucleotides in the RNA of an RNA bacteriophage (83), it may be presumed that a signal (perhaps AUG or GUG) is present in the phage RNA for initiating the translation at a proper site in the correct reading frame. In polygenic mRNA, such signals must occur at several sites.

Translation of Polygenic mRNA

The structural genes for the 10 enzymes of histidine biosynthesis, constituting the histidine operon, are adjacent to each other on the Salmonella typhimurium chromosome. The operon is transcribed into a single polygenic mRNA. The synthesis of all 10 enzymes can be repressed by histidine. When histidine-requiring mutants are grown on limiting amounts of histidine, the level of each enzyme increases about 25-fold. The rate of synthesis of the individual histidine biosynthetic enzymes was followed in cells which were first grown in a medium with excess histidine and then transferred into a medium in which histidine was limiting (derepression). Two modes of derepression were observed. About 20 min elapsed between the increase in the rate of synthesis of the first and the last enzyme when the level of the formyltetrahydrofolate pool (available for formylation of Met-tRNAf) was low. In these conditions, the order of the increase in the rate of synthesis of the individual enzymes was the same as the order of the corresponding genes on the chromosome [sequential translation (27, 28)]. Sequential translation of enzymes of the lactose (10, 77, 211), galactose (249), and tryptophan (165, 263) operons was also reported (99). This mode of gene expression presumably reflects translation starting from a single initiation site at the 5' end of the RNA. This may be a consequence of (i) the sequential transcription of the polygenic mRNA starting at the 5' end, (ii) the unavailability of internal initiation sites for ribosome attachment due, for example, to secondary structure of the mRNA, or (iii) the lower efficiency of the internal initiation sites than that of the one near the 5' end; furthermore, (iv), it might be that not each peptide chain initiation site is a ribosome attachment site as well, and that signals for ribosome attachment onto mRNA may include longer nucleotide sequences than do the signals for peptide chain initiation.

Remarkably, the increase in the rate of synthesis of all enzymes of histidine biosynthesis apparently occurred simultaneously under conditions in which the level of the formyltetrahydrofolate pool in the cells was high (27, 28). It has been shown that the histidine operon is transcribed into a single mRNA in conditions of either sequential or simultaneous translation (392). This observation, and the fact that it was the size of the formyltetrahydrofolate pool (presumably regulating the amount of fMet-tRNA) which determined whether the mode of translation was sequential or simultaneous, suggests that in this case the cause of the difference between the two modes of translation involves primarily the translation process itself and might, for example, be the consequence of having more efficient initiation sites at the 5' end of the mRNA than in internal positions. Simultaneous initiation of the translation of two different polypeptides was also observed upon adding f2 RNA to the in vitro E. coli system (221). The simultaneous mode of translation seems to require that ribosomes do attach simultaneously to several sites of the polygenic mRNA. Consequently, a free 5' end of the mRNA may not be a prerequisite for this attachment. In support of this conclusion, it has been shown that a circular messenger (i.e., one with no ends) promotes the binding of fMet-tRNA and amino acid incorporation into polypeptides (39). In the experiment proving this point, use was made of the curious fact that in the presence of certain antibiotics single-stranded DNA can be translated in vitro without prior transcription into RNA (244); the molecule used as messenger was actually the circular DNA of the bacteriophage fd.

Initiation Factors

The high nuclease activity in extracts from E. coli causes fast degradation of added synthetic mRNA. A system with somewhat lower nuclease activity can be prepared by washing the ribosomal pellet (resulting from the centrifugation of the cell extract at high speed) with ammonium chloride (0.5 to 2 M), purifying the washed ribosomes by chromatography on diethylaminoethyl cellulose, and mixing the purified ribosomes with the high-speed supernatant fraction (361). Such a system incorporates amino acids in response to synthetic messengers with or without initiator codons, at high Mg++ concentration; it is not active, however, at low Mg++ concentrations with any kind of messenger. Adding the ammonium chloride solution in which the ribosomal pellet was washed makes the system responsive at low Mg++ concentration to certain natural
mRNA or synthetic mRNA with initiator codons. Fractionation of the ribosomal washing solution led to the discovery of several complementary factors (presumably of protein nature) which are required at low Mg$$^{++}$$ concentration for the translation of mRNA with initiator codons. These factors are designated initiation factors (361; see also 37, 94, 319). Their function in translation will be discussed in subsequent sections.

**Exchange of Ribosomal Subunits During Protein Synthesis**

The 30S and 50S ribosomal subunits (separated from each other) have a unique role in initiation. These subunits are metabolically stable and remain intact in growing *E. coli* during several generations. The ribosomes undergo exchange of their 30S and 50S subunits. This exchange has been demonstrated by centrifugal analysis of the distribution of isotopic labels among ribosomes and their subunits after the transfer of a growing culture from a medium containing heavy isotopes to one containing light isotopes (167). Rapid and extensive subunit exchange also takes place during protein synthesis in a cell-free system. The exchange is dependent upon protein synthesis and is blocked by inhibitors of protein synthesis. The kinetics of the exchange suggest that ribosomes exchange their subunits after each passage over a polygenic mRNA or even over a single gene of the mRNA (166).

As an explanation for the exchange, it was presumed that ribosomes dissociate into subunits after finishing the synthesis of a protein molecule and are reformed by coupling of subunits when initiating the synthesis of a new protein molecule (166; see also 235). In line with this hypothesis (235) free 30S and 50S subunits have been found in lysates of *E. coli* cells along with 70S ribosomes and polyribosomes [i.e., structures in which several ribosomes are attached to and are translating a single mRNA molecule (108a, 186, 235, 309, 336a, 337)].

**Role of 30S Subunits in Initiation**

An early intermediate in initiation is apparently a complex including the 30S subunit, mRNA, and fMet-tRNA$$\text{F}_1$$. Some of the experimental results and considerations on which this conclusion is based are the following. Protein synthesis in vitro at low Mg$$^{++}$$ concentration (4 to 9 nm) seems to require proper chain initiation, i.e., fMet-tRNA$$\text{F}_1$$, initiation factors, and mRNA with properly located initiator codons. (In the absence of any one of these prerequisites, e.g., in the case of polyphenylalanine synthesis as promoted by poly U, a higher Mg$$^{++}$$ concentration is mandatory.)

At low Mg$$^{++}$$ concentration in the presence of initiation factors, f2 RNA or poly (A, U, G) promote the binding of fMet-tRNA$$\text{F}_1$$ to 30S subunits. In the same conditions, the binding of other AA-tRNAs (e.g., Val-tRNA) to 30S subunits is not stimulated by poly (A, U, G), although this messenger is rich in valine codons. [To obtain binding of Val-tRNA, 50S subunits also have to be added (285; see also 95, 155).] The complex containing a 30S subunit and fMet-tRNA$$\text{F}_1$$ is a compulsory intermediate for initiation, as shown by the following observations. "Heavy" ribosomes (70S) were prepared from *E. coli* (grown in a D$_2$O- and $^3$H-containing medium) by extracting the cells in conditions in which a large part of the ribosomes sediment as 70S components. These 70S "heavy" ribosomes were included in a reaction mixture containing, among other components, "light" 50S ribosomal subunits, poly (A, U, G), fMet-tRNA$$\text{F}_1$$, Val-tRNA, and initiation factors. After analyzing the reaction mixture after incubation by density gradient centrifugation, it was established that the majority of the fMet-tRNA$$\text{F}_1$$ was attached to hybrid 70S ribosomes, whereas most of the Val-tRNA was bound to "heavy" 70S ribosomes. These results indicate that 70S ribosomes must dissociate into their subunits preceding fMet-tRNA$$\text{F}_1$$ binding, although not preceding Val-tRNA binding (141).

**Process of Initiation**

Steps in initiation (Fig. 2). As indicated in the previous section, a complex including fMet-tRNA$$\text{F}_1$$, mRNA, and a 30S subunit ([285]; complex I) is apparently one of the early intermediates in peptide chain initiation. The formation of complex I requires GTP and initiation factors (9, 11, 95, 141, 153, 155, 207, 227, 265, 285, 331). Subsequently, a 50S subunit seems to attach to complex I (complex II). The fMet-tRNA$$\text{F}_1$$ in complex II is thought to be bound at the hypothetical site A of the ribosome (123, 189, 190, 265, 286, 336). In the next step, fMet-tRNA$$\text{F}_1$$ is believed to be translocated to site P, a second hypothetical site on the ribosome (complex III). There are indications that GTP may be cleaved into guanosine diphosphate (GDP) and orthophosphate (P) in the course of the transformation of complex II to III (187). The formation of complex III is the last step in chain initiation.

**Characteristics of initiation complexes.** The fMet-tRNA$$\text{F}_1$$ and mRNA bound to ribosomes (e.g., in complexes I, II, and III) may be distinguished from the free species by filtration through nitrocellulose filters; the bound species are retained on the filters, whereas the free species
Fig. 2. Schematic outline of steps in peptide chain initiation. (The steps are described in the text.) Symbols: n - 2, n - 1, n, n + 1, n + 2, a series of adjacent codons in the mRNA segment shown; n, initiator codon; "bottomless bracket," tRNAf; TP, N-formyltetrahydrofolate-Met-tRNAf-transformylase; fTHF, N-formyltetrahydrofolate; THF, tetrahydrofolate; IFs, initiation factors; E_Met, Met-tRNA synthetase. The oval shapes represent ribosomal subunits. A and P indicated in the 50S ribosomal subunit are hypothetical tRNA binding sites. CI (circled), etc., indicate the hypothetical intermediates described in the text.

Fig. 3. Schematic outline of steps in peptide chain elongation and termination. (The steps are described in the text.) Symbols: S1, S2, S3, elongation factors; "bottomless bracket," tRNA accepting AAi; ω - 2, ω - 1, ω, ω + 1, a series of adjacent codons in the mRNA segment shown; ω, a terminator codon; RFs, release factors. In CVII (circled), a polypeptidyl residue is attached to the tRNA. For other abbreviations, see the legend to Fig. 2.

are not (278). Free fMet-tRNAf, free mRNA, and complex I can also be separated from each other and from complexes II and III by centrifugation through a sucrose gradient.

The filtration assay is much faster than the one involving ultracentrifugation. This may account for the fact that a loose complex which is displayed as a complex in filtration may dissociate
at least partially into its components in the course of ultracentrifugation (190). Using these techniques, it was established that the coupling of 30S and 50S subunits to form 70S ribosomes (i.e., complexes II or III) strictly depends at 5 mm Mg++ on mRNA (actually, f2 RNA was used), fMet-tRNA$_F$ initiation factors, and GTP (190).

5'-Guanyl - methylene - diprophosphate (GMPPCP), an analogue of GTP, can substitute for the latter in the formation of complex I (11, 265) and in the subsequent attachment of the 50S subunit to this complex (189, 190). GMPPCP has a methylene bridge between the &gamma; phosphorus atoms and, thus, cannot undergo enzymatic cleavage into GDP and P$_i$ (152). The fact that it can substitute for GTP indicates that GTP cleavage need not occur before or during the initial attachment of a 50S subunit to complex I. The complex formed in the presence of GMPPCP and the complex formed in the presence of GTP behave similarly in the filtration test. However, the complex formed in the presence of GMPPCP largely dissociates in the course of centrifugation through a sucrose gradient (190) and does not react with puromycin (292), whereas the complex formed in the presence of GTP largely persists in the sucrose gradient test (190) and does react with puromycin, giving rise to fMet-puromycin (42, 206, 292, 331).

Puromycin and the tRNA binding sites of the ribosome. Puromycin is an inhibitor of protein synthesis which may be considered an analogue of the terminal aminoacyladenosine portion of AA-tRNA (417). Puromycin can react with peptidyl-tRNA (125) in the presence of ribosomes (262), giving rise to peptidyl-puromycin and free tRNA (258). This reaction may serve as a basis for defining different tRNA binding sites on the ribosome (388).

Poly-U-tRNA, whose synthesis is directed by poly U in the in vitro system, remains bound to the ribosomes (125). Ribosomes with bound peptidyl-tRNA can exist in two states. (i) In one state, they can react with puromycin (forming peptidyl-puromycin) without further additions. It is customary to define that such ribosomes have the peptidyl-tRNA attached to the peptidyl donor tRNA binding site (P site). (ii) Ribosomes with bound peptidyl-tRNA in the other state require addition of GTP and of the high-speed supernatant fraction for reacting with puromycin. Such ribosomes are said to have the peptidyl-tRNA bound to the AA-tRNA receptor site (A site). The supernatant fraction and GTP are required for catalyzing the translocation of the peptidyl-tRNA from site A to site P (258). In the course of this step, GTP is apparently cleaved into GDP and P$_i$ (see Translocation).

Site of binding of fMet-tRNA$_F$ to Ribosomes. FMet-tRNA$_F$ in the initiation complex formed in the presence of GMPPCP (as well as mRNA and initiation factors) does not react with puromycin (292). This seems to suggest that the initiator tRNA is not bound to site P of the ribosome in these conditions. Furthermore, tetracycline, an antibiotic inhibiting the binding of AA-tRNA to the A site (133), was found to block the binding of FMet-tRNA$_F$ to ribosomes in the presence of GTP, mRNA, and initiation factors (336). This suggests that FMet-tRNA is bound, at least initially, to site A.

FMet-tRNA$_F$ in the initiation complex formed in the presence of GTP (as well as mRNA and initiation factors) does react with puromycin (42, 206, 292, 331). This reveals that in these conditions FMet-tRNA$_F$ is bound to the P site [(388), complex III].

The above results, and the fact that the guanosine triphosphatase activity of an initiation factor (F2) is stimulated by FMet-tRNA$_F$, 30S and 50S subunits, mRNA, and other initiation factors, are consistent with, although they do not necessarily prove, the following sequence of events. FMet-tRNA$_F$ is attached to the A site first (complex II) and is subsequently translocated to the P site (complex III). GTP is cleaved before or during this translocation (187).

Role of initiation factors. Several complementary initiation factors have been isolated from crude preparations (45, 187, 232, 291, 301, 320). The relation of all the factors described by the various investigators remains to be established. The highest number of complementary factors reported from a single laboratory is four; some of these appear to consist of several nonidentical subunits (291).

At least some of the initiation factors can be found attached to native 30S subunits (95, 301). The same factors do not occur on either 70S ribosomes or free 50S subunits (301). This suggests that the factors are released from the 30S subunits sometime after the 50S subunit becomes attached to the 30S subunit in the course of initiation. Since initiation factors were not found in the high-speed supernatant fraction of the cell extract, it may be assumed that they are present in short supply, and as soon as they are released from 70S ribosomes they become bound to 30S subunits.

The order in which the components of complex I are associated is not known. The data available are in line with, but do not prove, the view that the binding of a 30S subunit to mRNA occurs first and is followed by the attachment of FMet-tRNA$_F$ (12, 45). Apparently, one or two factors (in addition to GTP) are involved in the attach-
ment of mRNA to the 30S subunit (45, 187, 291, 320).

It remains to be seen whether the positioning of a ribosome on an initiation sequence of the mRNA is assisted by fMet-tRNA_{F} or by initiation factors. It was reported that some of the initiation factors are needed for the translation of certain natural messengers, but not for that of synthetic messengers with AUG or GUG at or near the 5' end (291, 320). This raises the interesting possibility that the factors may recognize an initiation sequence longer than AUG or GUG. If such longer initiation sequences exist, they may serve as a basis for explaining the postulated occurrence of initiation sequences with different efficiencies (241).

There is no agreement between reports concerning, for example, the following problems (291, 320). Is the binding of mRNA and of fMet-tRNA_{F} to the 30S subunit mediated by the same initiation factor or by different ones? Is the attachment of the 50S subunit to complex I promoted by a factor also needed in forming complex I? It may be expected that with the availability of pure factors, these and other apparent discrepancies will be resolved.

Role of the formyl residue and of tRNAs in initiation. The following observations indicate that unformylated Met-tRNA_{F} cannot initiate protein synthesis in E. coli. Met-tRNA_{F} does not substitute for fMet-tRNA_{F} in allowing translation of f2 RNA in vitro at low Mg^{2+} concentration (96, 188). Protein synthesis in vivo stops if the formylation of Met-tRNA_{F} is inhibited (343). These results may be the immediate consequence of the fact that the initiation factors which promote the binding of fMet-tRNA_{F} to ribosomes in the presence of GTP and initiator triptolide do not promote the binding of unformylated Met-tRNA_{F} (332). The ultimate basis for blocking the α-amino group of the initiator tRNA is, however, presumably the substrate specificity of the enzyme catalyzing peptide bond formation (257).

AA-tRNA with a blocked α-amino group (other than fMet-tRNA_{F}) can substitute for fMet-tRNA_{F} in making amino acid incorporation at low Mg^{2+} concentration possible in vitro. In such conditions, amino acid incorporation directed, for example, by poly (A, U) depends strictly on added peptidyl-tRNA. It should be noted that the α-amino group of the C-terminal AA-residue is blocked in peptidyl-tRNA (267; see also 284). Poly U-directed polyphenylalanine formation at 4 mM Mg^{2+} concentration was found to take place only if N-acetyl-Phe-tRNA, as well as GTP and initiation factors, were present in the reaction mixture (227). This result and the fact that initiation factors do not recognize unformylated Met-tRNA_{F} as their substrate indicate that the factors or the components with which they interact recognize whether the α-amino group is blocked or not.

Transfer RNA_{F} and its derivatives are distinguished from other tRNA and their derivatives by the following enzymes: (i) the transformylase which formylates Met-tRNA_{F}, but not Met-tRNA_{M} (84, 237); (ii) the initiation factors and the 30S ribosomal subunit which appear to form a more stable complex with fMet-tRNA_{F} than with acetyl-Phe-tRNA (138); (iii) factors involved in peptide chain elongation which do not recognize fMet-tRNA_{F} or Met-tRNA_{F} as their substrate (295); (iv) an enzyme hydrolyzing N-acetyl-AA-tRNAs (81), which hydrolyzes fMet-tRNA_{M} (to N-formylmethionine and tRNA) but does not attack fMet-tRNA_{F} or acetyl-Met-tRNA_{F} (192, 395). This enzyme also hydrolyzes peptidyl-tRNA [at least one with a blocked α-amino residue (192)]. A possible function of this hydrolase is to destroy analogues of fMet-tRNA_{F} and to thus avoid false chain initiation.

Possible Involvement of fMet-tRNA_{F} in the Regulation of RNA Synthesis

In E. coli, the rate of net RNA synthesis (e.g., as measured by the incorporation of uracil from the medium into RNA) decreases to less than 10% of its normal value after the removal from the medium of an amino acid which cannot be synthesized by the cell. It is said, therefore, that net RNA synthesis is under stringent control of amino acids (RC^{+}). E. coli mutants exist in which RNA synthesis continues at about the normal rate after removal of a required amino acid. In mutants of this type, the control of RNA synthesis is apparently relaxed (RC^{−}). The inhibition of the charging of an amino acid onto tRNA affects RNA synthesis just like the removal of a required amino acid (91).

Either of two compounds which inhibit peptide chain initiation by preventing the formylation of Met-tRNA_{F} were also found to inhibit net RNA synthesis in RC^{+} E. coli, but not in RC^{−} E. coli. The two compounds are Trimethoprim and hydroxylamine, and each of these blocks fMet-tRNA_{F} synthesis by depleting the formyltetrahydrofolate pool. These results may indicate that net RNA synthesis in RC^{+} E. coli depends on the availability of all AA-tRNAs as well as fMet-tRNA_{F} (182, 343). Since the only process which is known to require all the above compounds is protein synthesis, it may be that net RNA synthesis is regulated by protein synthesis or by a step or intermediate in this process (293; see also 262a, 324a).

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Peptide Chain Initiation in Various Organisms

Prokaryotic cells. At least some of the proteins specified by bacteriophage T4-infected E. coli are initiated with N-formylmethionine (183, 184, 251).

Some of the prokaryotic cells, other than E. coli, in which the occurrence of fMet-tRNA is established are the following: B. subtilis (20, 162, 378), B. stearothermophilus (1, 295), Micrococcus lysodeicticus, pseudomonas aeruginosa, anacystis nidulans (a blue-green alga) (20), Mycoplasma laidlawii B, M. gallisepticum A 5969, and Mycoplasma species (caprine strain; 149). The dependence of the derepression pattern on the formylating capacity in salmonella typhimurium (27) and the fact that Met-tRNA from E. coli B can be formylated by extracts of lactobacillus leichmani, pseudomonas species, streptomyces antibiotics, and Clostridium tetanomorphum (84) suggest, but do not prove, the involvement of fMet-tRNA in protein synthesis in these organisms.

Eucaryotic cells. N-formylmethionine was reported as the N-terminal residue of the viral coat protein synthesized in a system containing Euglena gracilis chloroplast ribosomes, E. gracilis high-speed supernatant fraction, and f2 bacteriophage RNA (338). fMet-tRNA has also been found in mitochondria from yeast and rat liver (350). Protein synthesis in chloroplasts and mitochondria resembles that in bacteria in several ways. Thus, chloramphenicol and some other antibiotics inhibit chloroplast (93, 240, 303) and mitochondrial protein synthesis in vivo and in vitro (73, 193, 318), but do not seem to affect the cytoplasmic system from yeast and rat liver. Similarity among ribosomes from chloroplasts, mitochondria, and bacteria is suggested by the finding that all these particles have a sedimentation coefficient of about 70S, whereas that of the ribosomes from the cytoplasm is about 80S (34, 72, 194, 228, 365, 383). The existence of fMet-tRNA in mitochondrial, chloroplast, and bacterial systems may indicate that the same initiator is characteristic of 70S ribosomes in general.

fMet-tRNA has not been detected in the cytoplasmic system, and the initiator serving 80S ribosomes is not known.

Pyrrolidone-2-carboxylic acid has been shown to be an N-terminal residue in several proteins (311). It is an intriguing possibility that pyrrolidone-2-carboxylic acid may arise by the cyclization of a specific Gln-tRNA, which in turn serves as an initiator (30, 255). In view of the easy cyclization of glutamine to pyrrolidone-2-carboxylic acid, careful studies will be needed to examine this possibility. A number of proteins have N-acetylated amino acids as the N-terminal residue. An enzyme has been isolated from chicken reticulocytes catalyzing the transfer of the acetyl residue from acetyl-coenzyme A to certain proteins. This finding indicates that masking of the α-amino group of the N-terminal amino acid may occur after protein synthesis (236).

PEPTIDE CHAIN ELONGATION

Studies on peptide chain elongation in microbial extracts were greatly facilitated by the fact that at relatively high (presumably unphysiological) Mg++ concentration incorporation of aminoacyl residues from AA-tRNA into polypeptidyl-tRNA can be directed by natural or synthetic messengers (even if the latter lack initiator codons), and does not require either fMet-tRNA or initiation factors (96, 213, 218). The need for “proper” chain initiation is obviated at high Mg++ concentration, probably because in such conditions AA-tRNAs may attach to both the P and A sites of ribosomes bound to mRNA. If two AA-tRNAs are attached to the same ribosome, dipeptidyl-tRNA may be formed since the catalyst for peptide bond formation is part of the ribosome (see Peptide Bond Formation). Dipeptidyl-tRNA, in turn, is an analogue of fMet-tRNA and may serve as a chain initiator (218, 267; see Role of theformyl residue and of tRNA in initiation).

A simple system convenient for experiments on elongation is one in which the synthesis of a homopolypeptidyl-tRNA (e.g., polyphenyl-tRNA) is directed by a homopolyribonucleotide [e.g., poly U (279)]. In addition to the mRNA, AA-tRNA, proper ions, and thiols, such systems need to include ribosomes, GTP (176), and components of the high-speed supernatant fraction of the cell extract (271). To observe a strict dependence of amino acid incorporation on the high-speed supernatant fraction, the ribosomes have to be thoroughly washed. This treatment apparently removes from the ribosomes (among other substances) the factors required in elongation (271).

It should be noted that the large majority of elongation factor activity is in the high-speed supernatant fraction of microbial extracts (271). This is in marked contrast with the initiation factor activity which, as stated earlier, is exclusively located in the pellet obtained by centrifuging the extract at high speed.

Elongation Factors

Elongation factors were purified from the high-speed supernatant fraction of the extract of a number of bacteria and from yeast. Initially, two factors were found to be required for polypeptidyl-tRNA synthesis in E. coli extract, factor T and...
factor G (7). These two factors were also obtained in crystalline form (175, 302). More recently, the T factors from E. coli and from P. fluorescens have been divided into two active components, both of which are needed (together with factor G) in polyphosphate synthesis; one component is unstable (T_u), the other is stable (T_s, 226). Separated T_u and T_s form a complex with each other. In the presence of GTP, this complex apparently dissociates into a T_u-GTP complex and T_s (103, 250).

Three elongation factors (S_1, S_2, and S_3) were purified from the extract of a thermophilic organism, B. stearothermophilus. S_1 apparently corresponds to T_u, S_2 to T_s, and S_3 to T_u. All three partially purified B. stearothermophilus elongation factors are stable (349).

Elongation factors were prepared from E. coli extract also in the presence of phenylmethylsulfonylfluoride, an inhibitor of protein synthesis. In these conditions, two elongation factors were isolated, both of which are required in polyphosphate synthesis: factor E and a heat-stable protein. The exact relationship of these two factors to factors T and G is not known. It seems, however, that factor E contains some components of both factors T and G (161). Two elongation factors were obtained from the high-speed supernatant fraction of an E. coli extract which was treated with pHMB, a compound known to react with SH groups. One of the two factors is a protein which retains its activity even after boiling in acid. The factor is apparently not identical with either T_u, T_s, or G (421).

The variety of complementary elongation factors obtained from E. coli extracts treated in different ways may indicate that these factors are in a complex unit in vivo which can be artificially divided into sets of components in several ways. This possibility and the fact that a thorough and lengthy washing of the ribosomes is required in order to remove from them all of the elongation factor activity should admonish us to caution in interpreting the results obtained in the in vitro system. It may well be that the artificially disrupted system in which elongation is studied in vitro does not reflect faithfully the functioning of the elongation machinery in vivo. Complementary elongation factors were also isolated from yeast extract (19, 321).

**Process of Elongation**

**Outline of the steps in elongation.** A hypothetical scheme of steps in chain elongation is shown in Fig. 3. This scheme is based mainly on experiments with the T_u, T_s, and G factors from E. coli and the S_1, S_2, and S_3 factors from B. stearothermophilus. (Subsequently, whenever possible, the S_1, S_2, S_3 nomenclature will be used.)

The last step in peptide chain initiation is apparently the translocation of fMet-tRNA_{Phe} from site A to site P on the 70S ribosome-mRNA complex (cf. Steps in initiation). The first composite step in the next phase (i.e., peptide chain elongation) is presumably the attachment (to the vacant A site in complex III) of AA-tRNA specified by the codon adjacent to the 3' side of the initiator codon [AA-tRNA binding (168, 266, 278)]. The product of this step will be designated as complex IV. The attachment of AA-tRNA to complex III (which leads to the formation of complex IV) requires GTP and involves the factors S_1 and S_2 (102, 224, 314, 349). Results of in vitro experiments seem to indicate that GTP is cleaved to GDP and P_i in this step (296, 344).

Subsequently, the carboxyl group of the formylmethionyl residue of the fMet-tRNA_{Phe} is released from its linkage to tRNA_{Phe} and is linked in a peptide bond with the α-amino group of the AA-tRNA (peptide bond formation). In the product of this step (complex V), the fMet-AA-tRNA is located at site A (100, 101, 142). Peptidyl transferase, the enzyme catalyzing this reaction, apparently is part of the 50S subunit (256).

In the course of the next composite step (translocation), the following events are presumed to occur: (i) the discharged tRNA (in site P) is released from the ribosome; (ii) the fMet-AA-tRNA is shifted from site A to site P, and (iii) the ribosome moves the length of one codon along the mRNA in the 5'→3' direction (401). Translocation is catalyzed by an elongation factor (S_2). When studied in vitro the step also requires GTP which is cleaved to GDP and P_i (44, 100, 101, 142, 306, 381).

Thus, both AA-tRNA binding and translocation require the cleavage of GTP when studied in vitro. It remains to be seen, however, whether in vivo the cleavage of two GTP molecules is needed for the two steps or if cleavage of one GTP suffices.

After translocation, the stage is set for the addition of another amino-acyl residue to the fMet-AA-tRNA. Each addition requires the following cycle of events: AA-tRNA binding, peptide bond formation, and translocation. These events will be discussed in more detail in subsequent sections.

In the second cycle and in all the subsequent ones, peptidyl-tRNAs are taking the place of fMet-tRNA. The cycles are repeated and the peptide chain is growing, presumably until a terminator codon in mRNA is reached by the A site of the ribosome.
AA-tRNA Binding

The need for GTP and a factor (from the high-speed supernatant fraction of the cell extract) in attaching AA-tRNA to the mRNA-ribosome complex was first established in a cell-free system from reticulocytes (15). The requirement for GTP and a factor in catalyzing the same step in microbial systems was not revealed for quite a while. This delay was a consequence of the following facts. Chain elongation was studied mainly with poly U, which promotes polypeptide synthesis only at high Mg++ concentrations. At high Mg++ concentrations, in turn, there is a strong AA-tRNA binding which is independent of factors and GTP, and which may obscure the factor- and GTP-dependent binding (197, 314).

Recent binding experiments in the E. coli system (314) and the yeast system (19, 321) were performed, however, at lower Mg++ concentrations; under such conditions there is a need for GTP and supernatant factors in binding phe-tRNA to the ribosome-poly U complex (314). Apparently, two factors (S1 and S3) are involved in this step (102, 142, 349).

The following events are presumed to precede the binding of AA-tRNA to the ribosome. First, S1 and S3 form a complex with GTP (complex A). Complex A can be assayed conveniently since it is retained on nitrocellulose filters (8, 132, 315). The complex can be separated from free GTP by gel filtration (8, 349). Both S1 and S3 are required in complex A formation (102, 349); apparently the amount of S3 determines the quantity of GTP bound, whereas the amount of S1 determines the rate of complex formation (103). S2 is present in complex A, but it has not been definitely established whether S1 is also part of the complex. ATP is not bound by S1 and S3, whereas GDP is.

In a subsequent step, complex A apparently binds AA-tRNA and is transformed into a GTP-AA-tRNA-S1 complex (complex B) (132, 349). The formation of complex B from its components requires S1 (349). There are indications that S1 may not be part of complex B (316). This complex, in contrast to complex A, is not retained on nitrocellulose filters (132, 315). It can be separated from unbound GTP and AA-tRNA by gel filtration (349). The ratio of GTP and AA-tRNA in complex B is approximately 1:1 (131, 295). Binding of AA-tRNA in the complex depends strictly on GTP. GTP cleavage was not observed in the course of the formation of complexes A and B (131, 349). Most, and probably all, AA-tRNA species do form the complex (295). (For an important exception, see Problems Arising from the Dual Specificities of the AUG and GUG Codons.) The existence of competition between different AA-tRNA in binding indicates that the same S1 factor can bind different AA-tRNA species (295). Uncharged tRNAs is not bound in the complex and an excess of uncharged tRNA does not compete with AA-tRNA for binding (131, 295, 349). GDP and ATP do not substitute for GTP in making the binding of AA-tRNA possible (349).

There are indications that the GTP molecule in complex B is cleaved to GDP and P1 after the binding of phe-tRNA to the poly U-ribosome complex, but before peptide bond formation (296, 344). According to one report (296), the same partially purified S1 and S3 fractions from B. stea torhermophilus which promote the binding of AA-tRNA to ribosomes also catalyze the cleavage of GTP to GDP and P1 in the presence of ribosomes. This cleavage is promoted by the simultaneous presence of poly U and phe-tRNA. The ratio of GTP cleaved to phe-tRNA bound is approximately 1. Since it is known that in the presence of ribosomes the factor S3 also catalyzes the cleavage of GTP, it was ascertained that the GTP cleavage promoted by partially purified S1 and S3 is not due to S3 contaminating these factors; it was shown that fusidic acid, an antibiotic inhibiting the guanosine triphosphatase activity of S3, has no effect on the GTP cleavage catalyzed by S1 and S3 (296).

In another study (344), partially purified S1 and S3 factors from E. coli were used to form complex B with GTP and phe-tRNA. This complex was added to a reaction mixture containing poly U and ribosomes. Upon incubating this mixture, phe-tRNA became bound to ribosomes and about an equimolar amount of GTP was cleaved to GDP and P1. The resulting GDP was found in a complex with S3.

The following facts are consistent with the hypothesis that GTP cleavage occurs after the binding of AA-tRNA to the mRNA-ribosome complex but that it precedes the next step of chain elongation, i.e., peptide bond formation. (i) If GMPPCP (the analogue of GTP which cannot be cleaved enzymatically to GDP and P1) is substituted for GTP, phe-tRNA is bound to the ribosome-poly U complex in the presence of S1 and S3 but peptide bond formation does not take place, whereas in the presence of GTP it does (142, 296; see also 347). (ii) Sparsomycin, an antibiotic which blocks peptide bond formation (128, 260), does not inhibit either AA-tRNA binding (224, 296) or GTP cleavage catalyzed by the factors S1 and S3 (296).

It might have been expected that a compound such as tetracycline, which inhibits the binding of AA-tRNA to the mRNA-ribosome complex (133,
154, 336, 366), would also inhibit the promotion of the guanosine triphosphatase activity (of S₁ and S₃ in the presence of ribosomes) by poly U and phe-tRNA. Somewhat unexpectedly, it was found that tetracycline had no effect on the GTP cleavage (296). It remains to be seen whether this lack of inhibition is indicative of the existence of a loose binding of AA-tRNA to the ribosome which may occur in the presence of tetracycline and which is sufficient to promote the guanosine triphosphatase activity of S₁ and S₃.

S₃ may be recovered bound to the ribosomes if incubated in a reaction mixture including poly U, phe-tRNA, S₁, and GMPPCP. If, however, GTP is substituted for GMPPCP, S₃ cannot be found attached to ribosomes. These observations are consistent with the possibility that S₃ may become attached to the mRNA-ribosome complex together with GTP and AA-tRNA and is released from the complex after the GTP has been cleaved but prior to peptide bond formation. Since GMPPCP is not cleaved, S₃ remains attached (A. Skoultchi, Y. Ono, and P. Lengyel, in preparation).

GTP cleavage in the course of AA-tRNA binding to the mRNA-ribosome complex was first reported long ago by Schweet and his collaborators in experiments on the reticulocyte system (15; see also 245).

**Peptide Bond Formation**

After the attachment of AA-tRNA to the fMet-tRNA₆ₜ₆ribosome-mRNA complex in the first cycle of chain elongation (or to a peptidyl-tRNA-ribosome-mRNA complex in all subsequent cycles), the stage is set for peptide bond formation (Fig. 3). The peptide bond is formed between the carboxyl group of the fMet-tRNA₆ₜ₆ (or of the carboxyl terminal aminoacyl-residue of the peptidyl-tRNA) and the α-amino group of the AA-tRNA.

Some of the characteristics of the peptide bond-forming reaction are the following. Supernatant proteins and GTP are probably not directly involved (229, 256, 305, 388). Peptidyl transferase, the hypothetical enzyme thought to catalyze it, is apparently an integral part of the 50S subunit (229, 256, 258, 388). The presence of di- and monovalent cations (Mg²⁺ and K⁺ or NH₄⁺) is required for the reaction (259, 388). CpCpA, the 3' terminal nucleotide sequence common to all species of tRNA, seems to be involved in the interaction with peptidyl transferase of both the peptidyl-tRNA (in site P; 257) and the AA-tRNA (in site A; 330).

Most of these conclusions were derived from studies with substrate analogues which lack certain functional parts of the tRNA molecules but retain others. Puromycin, the most widely used of these, is an analogue of the terminal aminoacyl-adenosine moiety of the AA-tRNA. It contains that part of the tRNA which participates in peptidyl transfer, but lacks those parts which are involved in the codon specific binding to mRNA and binding to ribosomes. The peptidyl moiety of peptidyl-tRNA can be linked in a peptide bond to puromycin instead of to AA-tRNA. The resulting peptidyl-puromycin is released from the ribosomes (3, 125, 258, 262, 270, 417). Polyph-e-tRNA, the synthesis of which in vitro is directed by poly U, remains attached to ribosomes (125). Ribosomes, with attached polyph-e-tRNA, retain the ability to react with puromycin after having been washed with salt solutions under conditions similar to those which make ribosomes dependent upon the elongation factors and GTP for poly-peptide synthesis (229). This suggests that the elongation factors and GTP are not directly involved in peptide bond formation. This conclusion is reinforced in studies with ribosomes isolated free of mRNA and peptidyl-tRNA. Such ribosomes, even after thorough washing with salt solution, are still able to catalyze the reaction of puromycin with polylysyl-tRNA (in the presence of poly A; 329) or with fMet-tRNA (in the presence of, for example, the AUG triplet; 42, 424).

Lowering the Mg²⁺ concentration of a solution containing ribosomes with poly U and polyph-e-tRNA attached causes dissociation of the complex into 30S subunits and 50S subunits with bound polyph-e-tRNA (125). The fact that such charged 50S subunits can react with puromycin indicates that peptidyl-transferase, the enzyme catalyzing the reaction, is located in the 50S subunit (388). This conclusion is supported by experiments in which isolated, washed 50S subunits were found to catalyze the reaction of puromycin with CAACCA-fMet, a 3' terminal fragment of fMet-tRNA₆ₜ₆ (256). The reaction of puromycin with this fragment evidently takes place by the same mechanism as peptide bond formation in protein synthesis, since both reactions require the same mono- and divalent cations and the fragment reaction is inhibited by certain antibiotics [e.g., chloramphenicol, goguerin, and sparsomycin (406)] known to inhibit in vivo and in vitro protein biosynthesis (128, 256).

The fragment reaction requires the presence of alcohol (e.g., ethyl alcohol) for reasons not known at the present time (259).

The substrate specificity at the P site was studied by comparing the activity of various analogues of peptidyl-tRNA in the puromycin reaction (257). Various AA-oligonucleotides and acyl-AA-oligonucleotides were isolated from par-
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The results and considerations on which these conclusions are based include the following. The acPhe-tRNA was bound to a ribosome-poly U complex in the absence of initiation and elongation factors [at relatively high Mg++] concentration (142)]. The acPhe-tRNA ribosome-poly U complex was incubated with phe-tRNA, GTP, S1, and S2, and subsequently the ribosomes with the attached components were isolated from the reaction mixture by centrifugation. It was established (i) that the reisolated ribosomes have acPhe-tRNA attached, but no (or little) acPhe-tRNA. (ActriPhe-tRNA was not found in the supernatant fraction of the incubation mixture, either.); (ii) The large majority of the acPhe-tRNA did not react with added puromycin, indicating that it was bound at the A site. (iii) Discharged tRNA was sticking to the ribosomes (225), probably at the P site. These characteristics suggest that the above complex resembled complex V.

Upon incubating the isolated complex with GTP and S2, the discharged tRNA was released from the ribosomes (225; see also 195, 196, 340, 375) and most of the acPhe-tRNA became reactive with added puromycin, indicating that it was now located at the P site (142).

A portion of the complex was reisolated after the incubation with GTP and S2. After incubating this reisolated complex with S1, S2, Phe-tRNA, and GTP, the formation of actriPhe-tRNA was observed. Thus, the incubation with S2 and GTP made the A site available for binding Phe-tRNA, which in turn made tripeptidyl-tRNA synthesis possible (142).

In another study, AUGUUU and AUGUUUUUUU were used as mRNA in the E. coli system. The fMet-Phe-tRNA was synthesized in the presence of GTP, initiation factors, S1, and S2 (the last two not resolved from each other) in the presence of either mRNA; the formation of fMet-Phe-tRNA, however, also required S2 factor and occurred only in the presence of the tricodon mRNA (AUGUUUUUUU). The fact that the synthesis of fMet-Phe-tRNA required a tricodon as the messenger is consistent with the view that translocation involves a movement of the ribosome along the mRNA (100, 101).

These findings indicate that S2 is not needed for dipeptidyl-tRNA formation but that it is required for tripeptidyl-tRNA formation. The data are in accord with the view that the action of S2 results in (i) release of the discharged tRNA, (ii) translocation of the peptidyl-tRNA from the A site to the P site, and (iii) movement of the ribosome along the mRNA the length of one codon (218, 401). There is no cause to assume that translation...
of codons beyond the third would require additional factors.

The studies cited so far in this section provided some insight into the order of events in tripeptide synthesis and the role of the $S_2$ factor in this process. For assaying only $S_2$ activity, however, less-involved procedures are available. Each of these is based on one of the following observations. (i) As stated earlier, $S_2$ factor and GTP increase the fraction of ribosome-bound polyphenyl-tRNA which reacts with puromycin (388). (ii) At relatively high Mg$^{++}$ concentration, phe-tRNA may be attached to ribosome-poly U complexes in the absence of elongation factors. The fraction of the bound phe-tRNA, which is reactive with added puromycin, is increased several fold by incubating the complex with $S_2$ and GTP (44). (iii) At relatively high Mg$^{++}$ concentration in a system including ribosomes, poly U, and phe-tRNA, diphe-tRNA is synthesized in the absence of elongation factors, whereas the extensive synthesis of oligo-phe-tRNA (with more than two phe residues per molecule) depends on $S_2$ factor and GTP (306). (iv) $S_2$ factor, in the presence of ribosomes, cleaves GTP into GDP and P$_i$; this activity is stimulated by poly U and tRNA (75, 281, 282).

The following are some of the results and considerations which support the view that GTP cleavage by $S_2$ and ribosomes is connected to protein synthesis. (i) Fusidic acid, a steroidal antibiotic, inhibits both ribosome-dependent guanosine triphosphatase activity of $S_2$ factor and translocation (306, 381). Fusidic acid-resistant $E. coli$ mutants were obtained, and it was established that fusidic acid sensitivity or resistance is localized in the $S_2$ factor (179). (ii) GMPPPCP (the GTP analogue with a methylene bridge between the $\beta$ and $\gamma$ phosphorus atoms) does not substitute for GTP in translation; actually, in the presence of GTP, it acts as an inhibitor (44, 101, 142, 152, 306).

The incubation of ribosomes at elevated temperatures prior to using them in the guanosine triphosphatase assay in the presence of the $S_2$ factor results in the uncoupling of GTP cleavage from peptide synthesis; the rate of GTP cleavage increases slightly, whereas the rate of protein synthesis decreases sharply (75, 282).

Results were presented in an earlier section to indicate that GTP is cleaved in the course of peptide chain elongation after the attachment of AA-tRNA to the ribosomes but before peptide bond formation (296, 344). This guanosine triphosphatase activity of the $S_2$ and $S_3$ factors was first examined in a system free of $S_2$ activity (296). In more recent experiments, $S_3$ was also included in the reaction mixtures. It was established that the GTP added to the system in the form of the $S_2$-GTP-AA-tRNA complex does not make translocation possible (297). Thus, at least in the in vitro system with purified separated elongation factors, not less than two molecules of GTP are cleaved for the addition of each aminoacyl residue to the peptidyl-tRNA chain.

Efforts to establish the existence of a high-energy intermediate, whose formation is catalyzed by GTP and $S_2$ factor, have so far not been successful (281).

The availability of fusidic acid-resistant $E. coli$ mutants (179) and other mutants with a thermosensitive $S_2$ factor (387) will soon lead to the mapping of the chromosomal site of the gene specifying $S_2$.

**Problems Arising from the Dual Specificities of the AUG and GUG Codons**

As initiation codons, AUG and GUG specify fMet-tRNA$_F$ in the $E. coli$ system. As codons for internal aminoacyl residues of the peptide chain, however, AUG stands for Met-tRNA$_M$ and GUG for Val-tRNA$_V$. The dual specificities of AUG and GUG raise the question of how mixups of Val-tRNA, fMet-tRNA$_F$, and Met-tRNA$_M$ are avoided in protein synthesis. The outline of the answer is apparently the following. Val-tRNA and Met-tRNA$_F$ do not serve as initiators since they are not recognized by initiation factors. Furthermore, fMet-tRNA$_F$ does not participate in elongation; having its $\alpha$-amino group blocked, it cannot serve as a peptidyl residue acceptor. A more difficult problem arises with the methionyl residues (in Met-tRNA$_F$) which have a free $\alpha$-amino group and, in principle, could thus be mistakenly incorporated in the place of valine in response to GUG codons in chain elongation. Studies with in vitro systems (in which random poly(U, G) or poly(U, A, G) were used as mRNA) indicate, however, that Met-tRNA$_F$ (unformylated) does not serve as a source of methionyl residues for internal positions of the peptide chain (238).

The avoidance of this mistake apparently may be accounted for by the substrate specificity of the chain elongation factors $S_3$ and $S_4$; most and possibly all AA-tRNAs, including Met-tRNA$_M$, do form complexes with the factors $S_3$ and $S_4$ in the presence of GTP, whereas fMet-tRNA$_F$ and Met-tRNA$_F$ do not (295). The AA-tRNA-GTP-$S_3$ complexes are intermediates in AA-tRNA binding to the ribosomes. Thus, the lack of complex formation with Met-tRNA$_F$ may explain why Met-residues (from Met-tRNA$_F$) are not inserted into internal positions of the peptide chain in response to GUG codons.

The fact that Met-tRNA$_M$ does form a com-
plex with the elongation factors, whereas Met-

tRNA<sub>F</sub> does not, indicates that the factors dis-

criminate against tRNA<sub>F</sub>.

**PEPTIDE CHAIN TERMINATION**

During chain elongation, the growing polypep-

tide chain remains linked to tRNA and bound to

the mRNA-ribosome complex. After completion,

the polypeptide is released from both of these

bonds in the course of a composite process called

peptide chain termination (116, 191, 203, 376,

425). Termination is apparently triggered when in

the course of the movement of the ribosome along

the mRNA a chain termination signal is reached

at the A site of the 30S subunit (Fig. 3). It is

believed that the codons UAA, UAG, and UGA

(which are designated as nonsense codons) may

serve as chain termination signals (38, 333, 404,

405). Two release factors (R<sub>1</sub> and R<sub>2</sub>) were found

to be involved in this process. R<sub>1</sub> is specific for

termination coded by UAA or UAG, and R<sub>2</sub> for

that coded by UAA or UGA (58, 63, 339). After

release of the polypeptidyl-tRNA, the mRNA-

ribosome complex falls apart, giving rise to sub-

units (337, 403). There are some indications, 

although no conclusive evidence, that ribosomes

may actually be released from the complex as

dfree 70S ribosomes (2a, 186, 228a, 325) which are

subsequently dissociated into subunits, probably

by the action of a dissociation factor (369). Some

of the results and considerations on which the

above scheme is based are presented in the sub-

sequent sections.

**Termination Signals**

The codons UAA, UAG, and UGA do not seem to

specify any amino acid in *E. coli* strains

[unless the strains carry certain suppressor muta-

tions (117)]. These codons do not promote the

binding of any AA-tRNA to ribosomes (43, 355),

and a series of adjacent UAG or UGA codons in

a polynucleotide; e.g., poly (U-A-G) or poly

(U-G-A) does not direct in vitro amino acid

incorporation (178). [Actually, these two poly-

nucleotides do direct the formation of two homo-

peptides each, but these homopeptides are speci-

fied by the other codons in the RNA, i.e., AGU,

GUA, GAU, and AUG.) When occurring in

mRNA, the nonsense codons specify termination;

e.g., the synthetic oligonucleotide AUG-

UUUAAA directs the formation of fMet-phen-

ylalanine [not linked to trNA (203)]. RNA from

mutants of the bacteriophages f2 or R17 with a

UAG codon within the gene specifying the coat

protein promotes the synthesis in vitro of a coat

protein fragment (402), whereas RNA from the

corresponding wild-type phages directs the forma-

tion of the complete coat protein in vitro just as

it does in vivo (272). The approaches used in

identifying the nonsense codons and in decipher-

ing their nucleotide sequences were reviewed re-

cently (117).

**Release Factors and the Mechanism

of Termination**

Most of the information about the mechanism

of chain termination was obtained in two assay

systems. In one of these, RNA from a mutant

R17 or f2 phage with a UAG nonsense codon

early in the coat protein gene was used as the

message. In vitro, this messenger directs the

synthesis of the free (not tRNA-linked) amino

terminal hexapeptide of the coat protein (40, 58,

425). A cell-free system was prepared including

only those AA-tRNA species which are needed

for forming the hexapeptide. In this system, RNA

from wild-type phage directs the formation of

hexapeptidyl-tRNA, whereas RNA from the non-
sense mutant promotes free hexapeptide synthesis

(40, 58). Thus, if a codon is untranslatable in

sequence of the lack of a required AA-tRNA, this

leads to the stoppage of peptide chain

propagation but not to chain termination. The

fact that, in the presence of the mRNA from a

nonsense mutant, chain termination occurs even

in the absence of all tRNAs except the six species

added suggests that if RNA is involved in chain

termination, it is not contained in the tRNA

fraction (40, 58, 112, 352).

A substrate for studying the mechanism of

termination was prepared in the following way

(58). The formation of a hexapeptidyl-tRNA as

specified by the phage mutant RNA was blocked

at the pentapeptidyl-tRNA stage by omitting

from the in vitro system the amino acid coded by

codon 6. The ribosome-mRNA-pentapeptidyl-

tRNA complex was then separated from the

supernatant fraction by centrifugation and the

AA-tRNA needed to complete the hexapeptidyl-

tRNA was added in the presence of GTP. The

last amino acid became then added to the coat

protein fragment. The resulting hexapeptidyl-

tRNA remained attached to the mRNA-ribosome

complex. This product made possible the study of

the unique requirements of the release step. It was

found that the release of free hexapeptide from

this complex depends on a component from the

supernatant fraction. This component was
designated release factor (R factor) (58).

Recently, another convenient termination as-
say was developed. AUG, fMet-tRNA, and ribo-

somes were incubated to form an AUG-fMet-
tRNA-ribosome complex. The release of formyl-
methionine from this complex is promoted in the

presence of a crude R-factor preparation by each
of the three nonsense codons added in the form of triplets (63). By using this test, the R-factor preparation was separated into two components; R₁ catalyzes chain termination in response to UAA or UAG, and R₂ in response to UAA or UGA (339). The release of formylmethionine from fMet-tRNA by the R factors depends strictly on ribosomes.

The codon recognition pattern of R₁ resembles that found with some species of tRNA. The molecule interacting with A at the 3' terminal nucleotide position of the mRNA codon also interacts with G in this position. However, the codon recognition by R₃ has a pattern not found with any tRNA species so far. The R factors are nondialyzable and are inactivated on incubation with trypsin and N-ethylmaleimide, but not by ribonuclease. Thus, R₁ and R₂ behave like proteins with free sulfhydryl groups (339; see also 400).

The fact that the formylmethionine release from the ribosome in response to terminator codons is inhibited by tetracycline may suggest that these codons exert their terminating activity at the same ribosomal site of the 30S subunit where, in the course of elongation, AA-tRNA is attached. The lack of effect of fusidic acid on the release indicates that translacation, as catalyzed by the S₁ factor, is not involved in the process (339).

Fate of the mRNA-Ribosome Complex After Chain Termination

The fate of the mRNA-ribosome complex after chain termination was examined in vitro (403). The messenger in the system was ³²P-labeled RNA from either wild-type f₂ phage or from a mutant f₂ phage carrying a UAG nonsense codon in a known position of the coat protein-specifying gene. The technique used makes possible the monitoring of the translation of the mRNA by a single ribosome. First, asparaginase is added to the system to destroy asparagine. Subsequent addition of ³²P-labeled phage RNA results in the formation of a stable phage RNA-ribosompeptidyl-tRNA complex (with the ribosome stuck on the mRNA at a coding site for an asparagine residue on the coat protein gene). Further binding of ³²P-RNA to ribosomes is prevented by adding either an excess of unlabeled phage RNA or aurin-tricarboxylic acid. [The latter compound blocks attachment of ribosomes to mRNA and, consequently, initiation of new peptide chains, but it does not affect peptide chain elongation (135.)] Subsequently, asparaginase is added and, thus, synchronous translation of the coat protein gene ensues. The fate of the ³²P-f₂-RNA-ribosome complexes can be monitored by determining the amount of labeled RNA sedimenting as a complex with ribosomes (at the 80S region) and the amount sedimenting as free ³²P-RNA or ³²P-RNA attached to the 30S subunit (30S region and lighter). By using this technique, it was established that phage RNA and the polypeptide being synthesized rapidly disappear from the complex with the ribosome after translation of nonsense codons in the coat protein gene.

These observations seem to indicate that termination results in dissociation of the mRNA from the ribosome or, at least, dissociation of the 50S subunit, leaving behind an mRNA-30S subunit complex.

The release of the f₂ RNA from the complex is rapid, but only partial (about 20%), after termination at the end of the coat protein gene (in experiments in which the reattachment of ³²P-RNA to ribosomes is blocked by added excess unlabeled f₂ RNA). It is possible that this incomplete release reflects the translation of a subsequent gene on the mRNA by the same ribosome (or at least the same 30S subunit) which just completed the translation of the previous gene. Incomplete release occurs, perhaps, if the termination signal is near to an initiator codon (403). (For a discussion of related subjects, see references 57, 98, 225, 335, and 426.)

The hypothetical schemes concerning the fate of ribosomes in the chain termination complex (complex VII in Fig. 3) after the release of the completed polypeptide can be divided arbi-
trarily into two classes: (i) ribosomes released as free subunits and (ii) ribosomes released as 70S particles which subsequently dissociate into subunits (2a, 186, 337). If, among the products of chain termination, free 70S ribosomes (i.e., free of mRNA, peptidyl-tRNA, and fMet-tRNA) could be demonstrated, this would rule out the first class and be consistent with the second. 70S particles (in addition to subunits and polyribo-
some) have been detected in cell lysates (186, 228a, 309, 310, 325, 337). However, although the 70S particle (at least in principle) may be a free ribosome, it may also be a monosome (i.e., a complex of mRNA with a single ribosome with attached peptidyl-tRNA) or an initiation complex (a complex of mRNA with a single ribosome with attached fMet-tRNA).

According to some reports, 70S particles accumulate in cells that are incubated without a carbon source or treated with actinomycin (186). The latter treatment is believed to deplete the polysomes by blocking RNA synthesis. The fact that such 70S particles dissociate fully into subunits at an Mg²⁺ concentration (1 mM) at which monosomes dissociate only partially was taken as a support for the view that the 70S par-
ticles are free ribosomes (325). [Puromycin-treated 70S monosomes also dissociated at 1 mM Mg++ (325), and such ribosomes may carry attached discharged tRNA (225)]. Adding a protein fraction obtained from a 1 M NH4Cl solution used to wash native 30S subunits causes rapid dissociation of the presumed free ribosomes (369). The active component of the protein fraction was designated as a dissociation factor and appears to act on the ribosomes in a stoichiometric rather than in a catalytic manner. The dissociation factor resembles initiation factors at least in one aspect: it is present on native 30S subunits but not on 70S ribosomes (369). On the basis of these results, it was postulated that after chain termination ribosomes are released as free 70S particles (2a, 369) which are dissociated to subunits after reacting with a dissociation factor which combines with the 30S subunit. Apparently, the dissociation factor is released from the 30S subunit some time after the latter combines with a 50S subunit to form a 70S initiation complex (369).

According to other reports (309, 310), larger amounts of 70S particles can be detected in a lysate if it was prepared in the presence of K+ or NH4+ ions. However, such particles, or at least the majority of them, are artifacts; i.e., they are formed after cell lysis, probably by association of 30S and 50S subunits to form initiation complexes. Few or no 70S particles are detectable in lysates in which Na+ or Li+ are the monovalent cations, although preexisting 70S particles do not seem to dissociate in these conditions. Although these results seem to be in line with the first scheme, they cannot rule out the transient existence of free 70S ribosomes as intermediates in chain termination.

Further studies on the fate of the termination complex, which are underway in several laboratories, will help to resolve these apparent discrepancies.

PROBLEMS AND CONCLUSIONS

The following are a few of the outstanding problems in protein synthesis.

AA-tRNA synthetases. The principal aim is to understand the molecular basis of the high specificity of these enzymes for their cognate amino acid and tRNA. X-ray diffraction analysis of the enzymes of tRNAs, and, hopefully, of AA-tRNA synthetase of tRNA complexes may contribute to the solution of this problem. The detailed kinetics of the sequence of steps leading to the amino-acylation of tRNA remains to be determined. It is noteworthy that, although the reactions catalyzed by all the AA-tRNA synthe-
sases are analogous, the various enzymes in this group differ in many properties (e.g., molecular weight, effect of SH-reagents, etc.).

Transfer RNA. Although the nucleotide sequences of more than a dozen tRNA species have been determined, the anticodon and the CCA terminus are still the only regions of the molecule whose functions are established. The sites on the tRNA involved in recognition by the AA-tRNA synthetase, by the various tRNA binding sites of the ribosome, and by initiation and elongation factors all remain to be identified. In addition to X-ray diffraction studies, experiments with chemically or genetically altered tRNA molecules may facilitate the identification.

Much remains to be learned about the biosynthesis of tRNA. The chemical synthesis of tRNA-specifying genes (62, 342) may provide the basis for extensive studies on the transcription of these genes and on the modification of the products of the transcription (presumably the tRNA precursors) by the various modifying enzymes.

Further studies are needed on the role of tRNA in the regulation of protein synthesis, on the function of virus-specified tRNAs in the metabolism of virus-infected cells, and on the possible role of tRNA in differentiation and hormone action. The involvement of tRNA in bacterial cell wall synthesis proves that the function of this class of macromolecules is not restricted to protein synthesis.

Ribosomes. The chemical characterization of ribosomal proteins, together with the reconstitution of the 30S subunit, may provide the basis for the elucidation of the specific roles of the particular ribosomal proteins in ribosomes function. It is probable that a number of these proteins are serving as binding sites for AA-tRNA and peptidyl-tRNA and for initiation, elongation, and release factors. It is likely that eventually the techniques of electron microscopy and X-ray diffraction will become applicable to ribosome structure analysis.

Peptide chain initiation. Sequencing of natural mRNAs and of the RNAs of single-stranded RNA bacteriophages may be required for establishing the nucleotide sequence of ribosome attachment sites, peptide chain initiation and termination signals, and intercistronic regions. Instead of determining the complete nucleotide sequence of these RNAs, it may suffice to sequence those regions to which the ribosomes attach when initiating translation at various initiation sites of polygenic mRNAs. Presumably, attached ribosomes may protect the attachment sites on the mRNA against digestion by nucleases (377), and this may make the selective sequencing of such sites possible. Which component of the
protein-synthesizing machinery (ribosomal protein, initiation factors, fMet-tRNA, etc.) recognizes the initiation signals remains to be established.

The availability of pure initiation factors from E. coli should assist in determining the intermediate steps in initiation.

The process of initiation, the nature of the initiator tRNA, and the initiation signals in the cytoplasm of eukaryotic cells are not known at this time.

Peptide chain elongation. The requirement for GTP and the cleavage of GTP to GDP and P_i in the course of the addition of each aminoacyl residue to the growing peptide chain has been known for some time. Energetically, there seems to be no need for the free energy of GTP for peptide bond formation since the \( \Delta F \) of the peptidyl donor-peptidyl-tRNA (estimated to be \(-7\) kcal/mole) is ample for the formation of the peptide bond \( \Delta F = -3\) kcal/mole (218). Indeed, GTP is apparently not needed for the actual formation of the peptide bond in vitro.

The step in elongation that was first shown to require GTP is translocation (15, 75, 142, 218, 281). There is cause to believe that the GTP molecule needed for this step is cleaved prior to, or concomitantly with, the events in translocation. Recent data indicate that GTP is also required for AA-tRNA binding to the ribosome-mRNA complex and that cleavage of this GTP molecule may be a prerequisite for peptide bond formation (296, 344). Results of in vitro experiments suggest that the GTP cleaved in the course of AA-tRNA binding cannot serve in the translocation; i.e., at least two GTP molecules may be cleaved in the in vitro system for each aminoacyl residue incorporated into the growing polypeptide (297).

It may be too early to conclude that two molecules of GTP are cleaved for each peptide bond formed in vivo, too. One of the causes warranting this caution, too, is that in vitro conditions may create artifacts: The guanosine triphosphatase activity of S_2 (the translocase) as studied in vitro is apparently uncoupled from peptide bond formation. [More precisely, the S_2 factor catalyzes the cleavage of GTP just in the presence of ribosomes (75)]. It may well be that in vivo this is not the case.

It is an intriguing possibility, however, that translocation is a two-step process and that the cleavage of the first GTP may be needed to drive its first step. In the first step of such a hypothetical translocation model (after AA-tRNA binding and concomitantly with peptide bond formation), the 30S subunit, schematically speaking, moves along the mRNA the length of one codon, leaving the 50S subunit behind. (In the resulting intermediate, the discharged tRNA may be bound to the P site of the 50S subunit and the peptidyl-tRNA to the P site of the 30S subunit and to the A site of the 50S subunit.) In the second step (in which S_2 factor is involved and a second molecule of GTP is cleaved) the discharged tRNA is released, the 50S subunit is realigned with the 30S subunit, and the peptidyl-tRNA is shifted (from the A site to the P site of the 50S subunit). A two-step translocation model involving an intermediate similar to the one in this outline was proposed recently (41).

It remains to be established whether the GTP molecule(s) cleaved in the course of peptide chain elongation donate P_i or GDP to form a high-energy intermediate with a component of the translation machinery or whether the GTP(s) acts as an allosteric effector. It should be noted that the free energy of GTP could, in principle, drive ribosome movement even in an allosteric fashion (i.e., with no high energy intermediate of the X \( \sim \) P or GDP \( \sim X \) type involved). If binding of GTP would cause a conformational change of a protein and the cleavage of GTP would reverse the change, then a ratchet-type unidirectional movement could result from the repeated binding of GTP and its removal by cleavage to GDP and P_i.

Whatever the case, the mechanism of the movement of the ribosome relative to the mRNA and the role of GTP in this process are perhaps the most exciting unsolved problems in translation. A hypothetical model of ribosome function was proposed some time ago (358).

Peptide chain termination. Both genetic and biochemical studies indicate that each of the UAA, UAG, and UGA codons can serve as a signal in mRNA for chain termination. It is believed, however, that the normal and frequently used termination codon in vivo is UAA, and that UAG and UGA are rarely used, if at all. This assumption is based on the following facts and considerations. By genetic manipulation (more specifically, by introduction of nonsense suppressors) E. coli strains can be constructed in which UAG or UGA is frequently read as a chain elongation codon specifying an amino acid, instead of serving as a termination signal. Nevertheless, such strains grow normally. It is argued that if UAG or UGA would be principal chain termination signals, the growth of such strains would be adversely affected.

On the other hand, no strains have been found in which UAA would be translated with a high probability as an amino acid. Thus, it is believed that such strains may not be viable and, consequently, that UAA may be indispensable as a chain terminator codon (117).
The fact that two release factors are maintained in the cell, one of which is specific for UAG (in addition to UAA) and the other for UGA (in addition to UAA), may suggest that UAG and UGA are used as normal termination signals, even if rarely (339).

 Sequencing of natural mRNAs will be needed to establish definitely the nature of the termination signals.

 It also remains to be seen whether the release factors do recognize the termination signals directly, or whether other molecules, which in turn interact with the appropriate species of release factors (339), are involved in this process.

 In conclusion, it should be noted that the time is ripe for the application of the powerful methods of genetic analysis to the protein-synthesizing machinery. The first steps in this direction have been taken (129, 140, 179, 274, 337, 387). The selection of specific mutants, a prerequisite for such genetic studies, shall be greatly facilitated by the use of antibiotics [known to affect particular components of the machinery as selective agents (406)].

 The scope of this review has been restricted to microbial protein synthesis. It is obvious that the knowledge obtained by examining this pathway in microorganisms should accelerate the progress of similar investigations in higher organisms. The latter may contribute ultimately to the understanding of such diverse phenomena as antibody synthesis, hormone action, and differentiation.

 ACKNOWLEDGMENTS

 We thank J. R. Knowles, Y. Ono, A. Skoultchi, and J. Waterson for reading parts of the manuscript, and Nancy Benedict and Dorothy La Marche for patiently and repeatedly typing it.

 These investigations were supported by Public Health Service grants GM 13707 and GM 15401 from the National Institute of General Medical Sciences and by grant GB 7269 from the National Science Foundation.

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