

Architecture of Coatomer: Molecular Characterization of δ -COP and Protein Interactions within the Complex

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Abstract. Coatomer is a cytosolic protein complex that forms the coat of COP I-coated transport vesicles. In our attempt to analyze the physical and functional interactions between its seven subunits (coat proteins, [COPs] α - ζ), we engaged in a program to clone and characterize the individual coatomer subunits. We have now cloned, sequenced, and overexpressed bovine α -COP, the 135-kD subunit of coatomer as well as δ -COP, the 57-kD subunit and have identified a yeast homolog of δ -COP by cDNA sequence comparison and by NH₂-terminal peptide sequencing. δ -COP shows homologies to subunits of the clathrin adaptor complexes AP1 and AP2. We show that in Golgi-enriched mem-

brane fractions, the protein is predominantly found in COP I-coated transport vesicles and in the budding regions of the Golgi membranes. A knock-out of the δ -COP gene in yeast is lethal. Immunoprecipitation, as well as analysis exploiting the two-hybrid system in a complete COP screen, showed physical interactions between α - and ϵ -COPs and between β - and δ -COPs. Moreover, the two-hybrid system indicates interactions between γ - and ζ -COPs as well as between α - and β' -COPs. We propose that these interactions reflect in vivo associations of those subunits and thus play a functional role in the assembly of coatomer and/or serve to maintain the molecular architecture of the complex.

IN eukaryotic cells, intracellular traffic between membrane compartments is mediated by vesicular carriers (Palade, 1975; Rothman, 1994). Golgi-derived (COP I) coated vesicles can be produced in a mammalian cell free system that reconstitutes intercisternal protein transport (Balch et al., 1984; Balch and Rothman, 1985; Orci et al., 1986, 1989) and can be purified from such incubations (Malhotra et al., 1989; Serafini et al., 1991a). This led to the identification of their coat components, coatomer and ADP-ribosylation factor (ARF)¹ (Serafini et al., 1991b). Coatomer is a cytosolic protein complex that consists of seven subunits (coat proteins, COPs α - ζ) and that is recruited to the Golgi membrane during the budding of a transport vesicle (Waters et al., 1991). A similar complex has been identified in cytosol from yeast (Hosobuchi et al., 1992). All COPs except δ -COP are characterized at a molecular level. α -COP, $M_r = 135,000$, was defined as a protein in yeast that, when mutated (ret 1-1), leads to a defect

in retention/retrieval of ER proteins (Letourneur et al., 1994) and was cloned and sequenced independently to characterize the yeast homolog of mammalian α -COP (Gerich et al., 1995). Recently, the secretory yeast mutant sec 33 exhibiting an ER to Golgi transport defect was shown to bear a mutation in α -COP (Wuestehube et al., 1996). α -COP contains four WD40 repeats in its NH₂-terminal third. This motif was originally defined in the β -subunits of trimeric G-proteins and since was found in subunits of a whole variety of heteromeric protein complexes (Neer et al., 1994). Mammalian α -COP peptide sequences have been characterized from bovine brain and found to be highly conserved (Gerich et al., 1995).

Coatomer contains three subunits with molecular weights around 100 kD: (a) β -COP (Sec26p in yeast) (Duden et al., 1991, 1994; Serafini et al., 1991a), (b) β' -COP (Sec27p in yeast) (Harrison-Lavoie et al., 1993; Harter et al., 1993; Stenbeck et al., 1993; Duden et al., 1994), which, like α -COP, contains WD40 repeats; and (c) γ -COP (Sec21p in yeast) (Hosobuchi et al., 1992; Stenbeck et al., 1992; Harter et al., 1996). Mutations of these COPs in yeast cause an accumulation of ER membranes (Kaiser and Schekman, 1990), and mutated forms of Sec21p and of Sec27p lead further to a defect in retrieval of ER-resident membrane proteins, similar to ret 1-1 (Letourneur et al., 1994). This implication

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1. Abbreviation used in this paper: ARF, ADP ribosylation factor.

in ER retrieval has been suggested because coatomer is able to bind to peptides with a sequence motif -KKXXCO₂ (Cosson and Letourneur, 1994), known as signals for retrieval from the Golgi of escaped ER-resident membrane proteins (Nilsson et al., 1989). Although this binding has been attributed to a ternary complex of α -, β '-, and ϵ -COP in yeast and in mammals (Cosson and Letourneur, 1994; Letourneur et al., 1994; Lowe and Kreis, 1995), photo-cross-linking experiments have pointed to γ -COP as the KKXX-binding subunit of bovine coatomer (Harter et al., 1996). This discrepancy remains unresolved. Furthermore, the binding of γ -COP to a 20-kD protein (likely ζ -COP) has been shown (Lowe and Kreis, 1995). The same authors also suggest an association of β -COP to δ -COP. Most recently, a new mutant of *Saccharomyces cerevisiae*, RET-2, has been shown to be defective in retrieval as well as in forward transport between ER and Golgi, a mutation attributed to the δ -COP gene (Cosson et al., 1996).

Comparison of peptide sequences obtained from mammalian COPs isolated from both soluble coatomer and purified transport vesicles revealed that each COP is a constituent of the cytosolic coatomer as well as of the transport vesicle coat (Waters et al., 1991; Stenbeck et al., 1992; Kuge et al., 1993; Hara-Kuge et al., 1994). Both on vesicles and in coatomer, the individual COPs occur in a 1:1 stoichiometry (Waters et al., 1991; Serafini et al., 1991a), and the presence in transport vesicles of some of the COPs has been proven by immunoelectron microscopy (Orci et al., 1993; Stenbeck et al., 1993; Gerich et al., 1995). The coatomer subunits are recruited en bloc during the assembly of COP I coated vesicles (Hara-Kuge et al., 1994).

We wish to understand at a molecular level the mechanisms of the coating and budding reactions during the formation of a transport vesicle. Therefore, it is necessary to elucidate the molecular architecture of the coatomer complex. To this end, we have completed the structural characterization of coatomer subunits by cloning and sequencing the cDNAs for bovine δ -COP and α -COP. This has enabled us to test all seven COPs with each other for possible protein-protein interactions in the two-hybrid system, and we found four interacting pairs of COPs: β/δ -COPs, γ/ζ -COPs, α/ϵ -COPs, and α/β' -COPs. These results are in accordance with the suggested coatomer subcomplexes mentioned above and reveal novel binary COP-COP interactions: α/ϵ -COPs and possibly α/β' -COPs.

Materials and Methods

Strains, Media, and Microbiological Techniques

General molecular biological methods were as described (Sambrook, 1989). Yeast strain Y190 is MATa, ura3-52, his3-200, ade2-101, lys2-801, trp1-901, leu2-3, 112, GAL4-542, gal80-538, URA3::GAL-LacZ, LYS2::GAL-HIS3, cyh^r and was used for the two-hybrid system. RS453 (MATa/ α , his3/his3, leu2/leu2, trp1/trp1, ura3/ura3, ade2/ade2) was used for the δ -COP gene disruption and PCR experiments. Yeast was grown in YPD medium (1% Bacto-yeast extract, 2% Bacto-peptone, and 2% glucose) at 30°C. For selection of transformants, SD medium was used containing 0.7% nitrogen base, 2% glucose, and the appropriate amino acids.

Bacterial strains were *Escherichia coli* XL1 blue (Stratagene, La Jolla, CA) and *E. coli* M15 [pREP4] (Qiagen, Inc., Chatsworth, CA) for overexpression of δ -COP. Library screenings were performed in *E. coli* C600 Hfl and *E. coli* XL1 blue (Stratagene), subsequent cloning of the isolated DNA in CMK603 and *E. coli* XL1 blue (Stratagene).

Full-Length cDNA of α -COP

Screening a bovine liver cDNA library in uniZAP XR vector (Stratagene) expressed in *E. coli* XL1 blue MRF' (Stratagene) was performed using two degenerated ³²P-labeled antisense strand oligonucleotides coding for the peptides MIVFKLERERPA (amino acid residues 314–325) and QGNHOIVE (amino acid residues 684–691). From 10⁶ clones, two were detected as double positives in a filter screen. After in vivo excision, the resulting bluescript construct was sequenced with universal primers and several walking primers.

Full-Length cDNA of δ -COP

Screening a cDNA library λ gt10 (bovine brain) in *E. coli* C600Hfl was performed using a degenerated ³²P-labeled oligonucleotide coding for the peptide APVIGEIDGEY. This screening revealed the COOH-terminal 197-amino acid residues of δ -COP, the nucleotides 941–1536. To recover the whole cDNA sequence, the rapid amplification of cDNA ends (RACE) technique was used (Frohman et al., 1988). mRNA from bovine mammary gland was isolated with the polyAtract mRNA isolation system (Promega Corp., Madison, WI) and reversely transcribed according to the manufacturer's instructions (GIBCO BRL, Gaithersburg, MD) using primer 1. The resulting cDNA was used as a template for a PCR amplification step with the nested primer 2 for the COOH-terminal and an oligoA-universal primer for the polyT NH₂-terminal end. To obtain a specific product, a subsequent PCR with the universal primer and the nested primer 3 was performed. The obtained sequence did not reveal the NH₂ terminus of δ -COP, but an additional cDNA stretch of 155 nucleotides and oligonucleotide 4 was used to rescreen the λ gt10 library. The newly obtained cDNA sequence (from nucleotide 373 on) was used to design oligonucleotides for two further RACE reactions: first with primer 5 for reverse transcription, primer 6 and a polyA universal primer for the first PCR, and primer 7 and a polyA universal primer for the second PCR. Then with primer 5 for reverse transcription, primers 60N and 7 for the first PCR and primer 60N and 8 for the second PCR. Oligonucleotide 60N codes for the NH₂-terminal nine amino acid residues of δ -COP. The obtained clones all revealed the sequence from nucleotide 58 on, but not clearly the NH₂ terminus, which was finally found with another RACE reaction with Amplifinder Race (Clontech, Palo Alto, CA) using primer 9 for reverse transcription and primer 10 and an anchor primer for PCR, following the manuals suggested by the distributor.

To obtain the full-length cDNA, mRNA from bovine mammary gland was reverse transcribed with the COOH-terminal primer (TCGCGAAGCTTCTACAGAATTTTCATACTTATCCACTAGGA) containing a HindIII site and subsequent PCR with this primer and the NH₂-terminal primer (GCGCGGATCCTGGTGTCTGTTGGCAGCAGCAGTCTGTA) containing a BamHI site revealed the full-length cDNA of 1533 basepairs, which was subcloned into pQE32 (Qiagen) and sequenced. Primers were (with the position of nucleotides in brackets): 1 (1070–1094), 2 (1053–1076), 3 (1012–1036), 4 (856–885), 5 (440–465), 6 (413–438), 7 (391–415), 8 (368–394), 9 (263–289), and 10 (234–260).

Disruption of the δ -COP Gene

A DNA fragment containing full-length yeast δ -COP and additional flanking regions was constructed via PCR from genomic DNA of yeast strain RS453. Primers were GTACTTTACTATGTGGGTACGTATT-TAAGGTGGCA for forward and TTCCAGGTGCAATACTACTTGCACACAGGCG for reverse priming. The obtained 2,250-bp fragment containing the δ -COP gene and 224-bp downstream and 387-bp upstream was digested with ApaI and subcloned into the SmaI/ApaI sites of pBlue-script-SK⁺ (Statagene) vector. An internal 1396-bp NdeI/BglII fragment of the δ -COP gene was removed from the pBlue-script- δ -COP plasmid and replaced by the HIS3 gene (1.2 kb) after filling in the restricted ends. 20 μ g of the resulting plasmid was digested with BamHI and ApaI and transformed in *S. cerevisiae* strain RS453 by the lithiumacetate method (Gietz and Schiestl, 1991). The HIS⁺ transformants were isolated and analyzed by Southern blotting: 2 μ g of genomic wildtype and mutated DNA was digested with HindIII and XbaI, separated by agarose gel electrophoresis and blotted on nitrocellulose. A random-primed [³²P]dCTP-labeled DNA probe obtained from a BglII/ApaI 421-bp 5'-end fragment of the δ -COP gene was used for hybridization. Transformants were sporulated on YPA plates (1% Bacto-yeast extract, 2% Bacto-peptone, and 1% potassium acetate) and tetrad analysis on YPD plates was performed to separate mutant and wildtype alleles (Rose et al., 1990).

Overexpression of δ -COP

The full-length cDNA of δ -COP was ligated into pQE32 (Qiagen) with BamHI/HindIII and used to perform overexpression in *E. coli* M15 [pREP4] (Qiagen) as follows: a 700-ml overnight culture (37°C) of a positive colony (tested previously by Western blotting) in LB medium (Sambrook, 1989) supplemented with kanamycin (25 μ g/ml) and ampicillin (100 μ g/ml) was used to inoculate 7l LB Kana/Amp and was grown at 37°C to an OD₆₀₀ of 1.6. This culture was then induced with 15 μ M IPTG (isopropyl- β -thiogalactopyranoside, Gerbu Biotechnik GmbH, Gaiberg, Germany) and grown for 3 h at 30°C. A control culture was grown under the same conditions without induction (these cultures were used to compare the induced and uninduced cell extracts on a 7.5% SDS-PAGE). Cells were then harvested by centrifugation (8,900 g for 8 min, 4°C) and resuspended in 30 ml breakage buffer (50 mM Hepes, pH 7.0, 100 mM KOAc, 1 M NaCl, 10% glycerol).

Breakage of cells was done in a French press three times. Insoluble protein was separated by centrifugation of the cell lysates at 150,000 g for 30 min at 4°C. The supernatants were dialyzed against 50 mM Hepes, pH 7.2, 500 mM NaCl, 10 mM imidazole, 10% glycerol, 1 mM PMSF, and 2 mM benzamide. Further purification was performed using a Ni²⁺-chelating matrix (Qiagen) following a protocol suggested by the distributor, and the obtained protein was analyzed by Western blotting.

Two-Hybrid System

Transformations were performed by the lithium acetate method (Gietz and Schiestl, 1991), and selective medium was SD (6.7% nitrogen base without amino acids [Difco Laboratories, Inc., Detroit, MI], 2% glucose) supplemented with Adenine sulfate 20 mg/l, L-lysine-HCl 30 mg/l, and (if selection was not desired) L-histidine-HCl 20 mg/l. After growing for 3–4 d, 8–10 transformants were replica plated both on SD+His and SD–His + 25 mM 3-amino-1,2,4-triazole (3-AT; Sigma Immunochemicals, St. Louis, MO) and monitored for β -galactosidase activity by the filter lift assay (Breen and Nasmyth, 1985). All positive (blue) transformants were growing on the SD–His+3-AT. Quantification of β -galactosidase activity was performed by growing a 100-ml culture in SD+His medium to an OD₆₀₀ of about 2. The cells were centrifuged (5 min 500 g, 4°C), and the pellet was resuspended in 1 vol of water, resuspended in 500 μ l buffer B(400) supplemented with 1 mM PMSF and 2 mM benzamide, frozen/thawed in liquid nitrogen, and finally broken with glassbeads (size 0.5 mm) in a mini bead beater (three times for 90 s, 4°C). Buffer B(400) is 50 mM Tris-Cl, pH 7.5, 400 mM NaCl, 1 mM EDTA, 0.5 mM DTT, and 10% glycerol. After centrifugation (14,000 g), the supernatant was assayed for protein concentration and 50–100 μ g of total protein was assayed for β -galactosidase activity with ortho-nitrophenyl- β -D-galactoside (ONPG) as described (Guarente, 1983). The OD₄₀₅ was measured at at least four time points, and the β -galactosidase activity was determined as follows: 1 U = Δ OD₄₀₅ \times 1,000/mg protein \times time (min). Standard deviations were in the range of 10–20%.

Quantitative measurement of growth in SD–His + 25 mM 3-AT was performed by growing 50-ml overnight cultures to an OD₆₀₀ of 0.5–1.0. Fresh medium (100 ml) was inoculated to an OD₆₀₀ of 0.01, and the OD₆₀₀ was determined every 4–6 h. Generation times were measured in the range of OD₆₀₀ 0.1–0.8.

Antibodies

Antisera against a synthetic internal peptide of bovine δ -COP, RPS-GPSKALKLKGAKGKE (amino acid residues 216–232), and against the COOH-terminal peptide of bovine α -COP, KDVIGLRISPLQFR, were raised in rabbits. The peptides were coupled to keyhole limpet hemocyanin by glutaraldehyde (Harlow and Lane, 1988) and affinity purification of the δ -COP antibody was performed using the peptide coupled to epoxy-activated Sepharose 6B (Pharmacia LKB Biotechnology Inc., Piscataway, NJ). For immunoprecipitations, antisera against α - and δ -COPs were used, as well as anti- β' -COP-antiserum (Harter et al., 1993) and anti- ϵ -COP-antiserum (Hara-Kuge et al., 1994).

Immunolocalization

For electron microscopic immunolocalization, Golgi fractions from rat liver and CHO cells were fixed with 1% glutaraldehyde in phosphate buffer, infiltrated with 2.3 M sucrose, and processed for cryoultramicro-

omy according to Tokuyasu (1986). Sections were incubated overnight with affinity-purified anti- δ -COP antibody (undiluted). The antibody was revealed with the protein A–gold method (Roth et al., 1978). After immunolabeling, sections were absorption-stained with uranyl acetate (Tokuyasu, 1986) and examined in the electron microscope.

Plasmid Constructs

Fusion constructs with the cDNA of the GAL4 DNA-binding domain (plasmid pAS1) and with the GAL4 activation domain (plasmid pACT II) were obtained by in frame ligation of PCR products of β , β' , γ , δ , ϵ , and ζ -COP. The primers were designed to give a NcoI/SmaI product for β -COP, a SmaI/BamHI product for β' -COP and NcoI/BamHI products for γ -COP, δ -COP, ϵ -COP, and ζ -COP. Template for the PCR of δ -COP was the cDNA inserted in pQE32 (Qiagen), the same vector that was used for sequencing and performing the overexpression of the (6xHis)-tagged protein. For the PCR of β -COP, the template was the β -COP cDNA inserted in pGEM4Z (Promega), a gift from Dr. T.E. Kreis (University of Geneva, Switzerland) (Duden et al., 1991). The γ -COP cDNA is described (Harter et al., 1996). The cDNA of ϵ -COP in bluescript pSK⁺ (Stratagene) (Hara-Kuge et al., 1994) and ζ -COP in bluescript pSK⁺ (Stratagene) (Kuge et al., 1993) were generous gifts from Dr. J. Rothman (Memorial Sloan Kettering Cancer Center, New York). The fusion of α -COP with the DNA-binding domain of GAL4 was obtained by ligating an EcoRI/SalI fragment obtained from the full-length clone after subcloning in pQE30 (Qiagen) and M13mp18 (Promega) into the EcoRI/XhoI sites of the pBD-GAL4 vector (Stratagene). The fusion construct with the activating domain of GAL4 was obtained from the same cDNA fragment by ligating it into the pAD-GAL4 vector (Stratagene), followed by phage isolation and in vivo excision following the manuals of the distributor.

In Vitro Translation

mRNAs were in vitro transcribed from the cDNA of δ -COP inserted in pGEMT (Promega) and of β -COP (Duden et al., 1991) in pGEM4Z (Promega), of α -COP (this work, inserted in pbluescript SK), and ϵ -COP in pBluescriptSK (Hara-Kuge et al., 1994). Transcriptions were performed with T3 RNA polymerase (Promega; for β - and δ -COPs) or with T7 RNA polymerase (Promega; for α - and ϵ -COPs) following the protocol suggested by the distributor. The obtained mRNA was chloroform/phenol extracted and precipitated with ethanol/0.9 M ammonium acetate and resuspended in water.

In vitro translation was performed with the Flexi Rabbit Reticulocyte Lysate System (Promega) following a protocol suggested by the distributor. RNase inhibitor (Promega, 1 U/ μ l) and dithiothreitol (DTT, final concentration 1 mM) were added to all reactions. ³⁵S-labeled L-methionine (Amersham Corp., Arlington Heights, IL; 1,000 Ci/mmol) was added for radioactive labeling (final 1–2 μ Ci/ μ l). Reaction time was 90 min; longer incubations resulted in no increase of labeled protein, and shorter incubations did not result in less fragmentational translation. The yield of translated protein was detected by TCA precipitation as follows: 1 μ l of the sample was dried on a Whatman paper (10 min at room temperature), incubated in 10% TCA (5 min), and then boiled in 10% TCA (5 min). After washing with EtOH and drying (10 min at room temperature), radioactivity was quantified in a liquid scintillation counter.

Immunoprecipitation

Antibodies were coupled to protein A–Sepharose beads (CL4B, Pharmacia) as follows: Beads were washed five times with IP buffer (25 mM TrisCl, pH 7.4, 100 mM NaCl, 1 mM EDTA, 0.5% NP-40, 1 mM PMSF, 2 mM benzamide) and resuspended with two vol IP buffer. 300 μ l of this suspension (100 μ l beads) was incubated with 50 μ l antiserum or preimmune serum for 8 h, 8°C with agitation. After washing five times with IP buffer, the beads were resuspended in two vol IP buffer and were incubated as follows: all cups were preincubated for 1 h with BSA, 1 mg/ml, and BSA was added to the reactions to a final concentration of 0.1 mg/ml. 10 μ l of a 100,000 g supernatant (45 min at 4°C) of the translation assay was mixed with 30 μ l of suspended beads to a final volume of 50 μ l IP buffer and incubated for 18 h, 4°C with agitation. After washing the beads five times with IP buffer and twice with IP buffer containing no NP-40, the pellet was resuspended in 20 μ l SDS-PAGE loading buffer and 7 μ l were separated on a 7.5 or 10% acrylamide gel under reducing conditions.

Table I. Comparison of Bovine δ -COP with Homologue Proteins

Homologue	Species	M _r	Identity	Similarity	Features
		$\times 10^3$	%	%	
ARCNI	<i>Homo sapiens</i>	57.1	98	99	Presumably δ -COP
YFM1	<i>S. cerevisiae</i>	60.6	33	56	Coatomer subunit, δ -COP
AP 50	<i>S. pombe</i>	50.8	20	44	Subunit of the clathrin adaptor complex (AP2)
AP 47	<i>Mus musculus</i>	48.5	19	48	Subunit of the clathrin adaptor complex (AP1); kinase-activity

Sequence homologies of bovine δ -COP with its human and yeast homologs and with two subunits of the clathrin adaptor complexes: AP47 from mouse, AP1, and AP50 from *S. pombe*, AP2.

To this end, a 1.4-kb fragment of the coding sequence of yeast δ -COP was replaced by the HIS3 gene. A construct containing the disrupted copy was used to generate a diploid yeast strain RS453 with one wild-type and one mutant copy of the gene. Disruption was confirmed by Southern blot analysis (Fig. 4 A). Replacement clones were sporulated, and tetrads of each were analyzed as depicted in Fig. 4 B: a 2:2 viable/nonviable pattern was obtained. (No microcolonies were observed to grow out of the nonviable spores.) This result shows that δ -COP is encoded by an essential gene.

Primary Structure of Bovine α -COP

With the molecular structure of δ -COP described above, six of the seven COP cDNAs were available from bovine origin; however, α -COP at this time was only characterized in yeast (Letourneur et al., 1994; Gerich et al., 1995). For a complete screen for COP-COP interactions in the yeast two-hybrid system, we had to clone bovine α -COP as well. This was performed using a UniZapXR cDNA library from bovine liver (Stratagene) and degenerated ³²P-labeled oligonucleotides. The corresponding amino acid sequence was obtained by microsequencing peptides obtained by trypsin digestion of gel-isolated α -COP. The resulting cDNA derived amino acid sequence of α -COP and an alignment with the yeast homolog is depicted in Fig. 5. As expected from peptide sequence comparisons (Gerich et al., 1995), the derived amino acid sequence of yeast and bovine α -COP show a high degree of conservation (46% identity and 64% similarity). An open reading frame for

the human homolog of α -COP (accession number U24105) was identified by a database research with the bovine sequence reported here.

COP Interactions in the Two-Hybrid System

The complete set of the seven bovine COP cDNAs could now be analyzed in the yeast two-hybrid system (Fields and Song, 1989; Chien et al., 1991; Durfee et al., 1993) to identify binding partners of each COP within the coatomer complex. Two independent screens were performed: one with the cDNA of a given COP fused to the DNA-binding domain of GAL4 (BD, amino acid residues 1–147), searching for possible binding partners among the individually coexpressed COP proteins fused to the activating domain of GAL4 (AD, amino acid residues 768–881), and a second one with exchanged hybrid vectors (the COP was linked to GAL4[AD] and the other COPs fused to GAL4[BD]). In each set of experiments, 8–10 independent transformants were assayed for β -galactosidase activity and growth on a minimal medium that lacks histidine. β -galactosidase activities were monitored in a filter lift assay (Breedon and Nasmyth, 1985) and quantified by measurement of β -galactosidase activity units in cell extracts of the corresponding transformants. Response of the second reporter gene, HIS3, was analyzed by growth experiments on a His-selecting medium and also quantified by measurement of the generation time in this medium. As a positive control, a transformant was used that coexpresses SNF1/GAL4(1–147) and SNF4/GAL4(768–881), two proteins known to physically associate in vivo and whose interaction can be detected using the two-hybrid system (Fields and Song, 1989; Durfee et al., 1993).

This complete screen (49 different combinations of COPs) revealed four COP-COP interactions: β/δ -COPs, γ/ζ -COPs, α/ϵ -COPs, and α/β' -COPs. These results, together with the corresponding controls, are summarized in Table II. Each COP fusion protein alone cannot significantly activate GAL4-dependent transcription by itself in either fusion orientation, except ζ - and β -COP when fused to GAL4(BD). This transcriptional activation, e.g., in the case of ζ -COP, may result from acidic regions of the polypeptide (since it was not observed when ζ -COP is fused to GAL4[AD]), but still there is a significant stimulation of transcriptional activity resulting from the interaction with γ -COP (62 β -galactosidase units from ζ -COP alone in contrast with 812 units resulting from the interaction with γ -COP, see Table II). Except the α/β' -COP interaction, all binding COP pairs were detected in both fusion orientations. In the experiments with α -COP, either

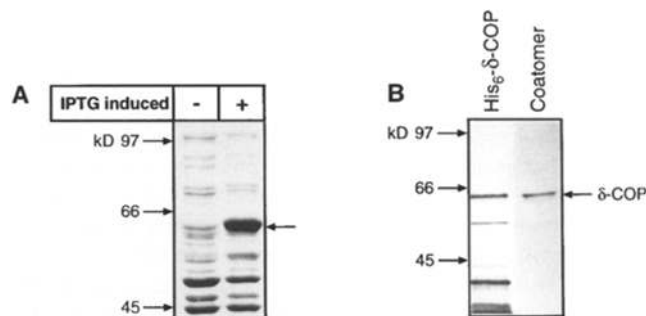


Figure 2. Overexpression of (6xHis)-tagged δ -COP. (A) Coomassie staining of equal amounts induced and uninduced lysates of *E. coli* separated on an SDS gel. (B) Immunostaining of an induced *E. coli* lysate with anti- δ -COP antibody (sample equivalent to 60 μ l of the culture). In the right panel, ~ 0.3 μ g of coatomer isolated from bovine brain was analyzed as a standard for δ -COP.

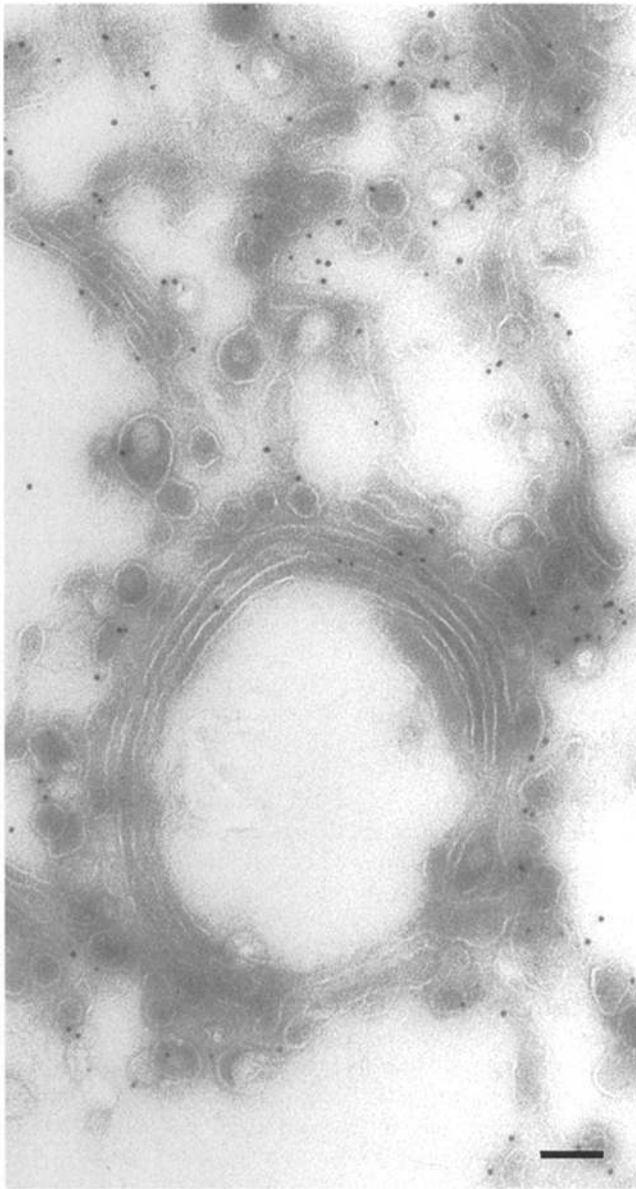


Figure 3. Immunoelectron microscopic localization of δ -COP antibody on Golgi-derived buds and transport vesicles generated in presence of GTP γ S from rat liver membranes. Affinity-purified anti- δ -COP antibody revealed by the protein A-gold technique. Size of gold particles 10 nm. A comparable labeling was obtained on Golgi fractions isolated from CHO cells. Bar, 100 nm.

in the pBD-GAL4 or pAD-GAL4 plasmid (both plasmids from Stratagene) and ϵ - or β' -COP in the partner plasmid, the transformants had an elevated β -galactosidase activity; however, these signals were much lower compared to the magnitude of increase of the growth ability in His-selective medium. This may be due to an inhibitory effect on the β -galactosidase activity of α -COP expressed in these transformants. Therefore, those values are not shown. However, these transformants showed highly significant growth in His-selective medium (Table II).

To identify possible interactions between COPs and the small G protein ARF (which is also a component of the coat of COPI-coated vesicles and probably binds

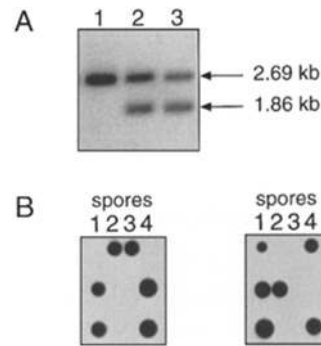


Figure 4. Analysis of δ -COP gene disruption. (A) Southern blot analysis of the HindIII/XbaI digested genomic DNA of the wild type (lane 1) and two mutant transformants (lanes 2 and 3). The 2.69-kb fragment is from the wild-type allele, and the 1.86-kb fragment from the mutant allele. (B) Tetrad analysis of the two mutant transformants shown in A. Of the four spores, only the two carrying the wild-type allele are able to grow.

coatamer), the cDNAs of ARF and a mutant form of ARF, mARF(Q71L) (Tanigawa et al., 1993), were screened against the individual COPs. The mutant form of ARF has lost the ability to hydrolyze GTP and therefore is fixed in the GTP-bound conformation in which it is known to bind to the membranes. From these experiments, no significant signals were obtained (data not shown), which may be due to the fact that ARF in the GTP-bound (activated) conformation possibly binds to membranes and is therefore not suitable for the two-hybrid assay.

Since the WD40 domains are known to be involved in protein-protein interactions (Neer et al., 1994), we tested this repeat domain of β' -COP with all COPs in both fusion orientations. No significant signals were obtained that would indicate any COP interactions with this motif (data not shown).

Coimmunoprecipitations of Binary COP Complexes

To biochemically characterize COP-COP associations as indicated by the two-hybrid experiments, we examined whether *in vitro* translated COPs could be coimmunoprecipitated. α - and ϵ -COPs, as well as β - and δ -COPs labeled *in vitro* by transcription/translation of the corresponding cDNA clones were incubated pairwise with the antibodies as depicted in Fig. 6, A and B. Anti- α -COP antibody precipitated *in vitro* translated α -COP (Fig. 6 A, lane 5), but not ϵ -COP (lane 6). However, if α -COP was cotranslationally synthesized together with ϵ -COP, both COP proteins were coimmunoprecipitated (Fig. 6 A, lane 4). In control reactions with preimmune serum, no labeled proteins were precipitated (Fig. 6 A, lane 7).

When β - and δ -COPs were *in vitro* cotranslated, a dimer of these coatamer subunits was immunoprecipitated with anti- δ -COP antibodies (Fig. 6 B, lane 4). Interestingly, the binary complex of β - and δ -COP was only precipitated from a cotranslated sample; however if the proteins were *in vitro* translated separately and then mixed, no coimmunoprecipitation of β -COP was observed with anti- δ -COP antibodies (not shown). In the case of α/ϵ -COPs, however, it was possible to coimmunoprecipitate the binary complex with anti- α -COP antibodies not only from a cotranslated sample but also from separately translated and subsequently mixed samples (not shown). No dimerization was observed when the pair of β' - and ϵ -COPs was analyzed, neither with anti- β' -COP nor with anti- ϵ -COP anti-

bovine 1 ..MLTKFETKSARVKGSLSEHPEKREWILTSLHNGVIQLWDYRMCTLLDKFD 48
 yeast 1 MKMLTKFESKSTRAKGIAPHSPRPVWLVVAFSSITQLWDYRMGTLLHRFE 50

bo 49 EHDGPRVGRIDPHKQPLFVSGDDYKIKVWYKLRRLCLFLLGHLDYIRT 98
 ye 51 DHEGPRVGRGLDHPHTQPTFVSGADDTYIKVWYSLDTRKCLYTLTGHLDYVRT 100

bo 99 TFFHHEVPWILSASDDQTIKRWVWQSRCTCVCVLIGHNHVYVCAQFHPSED 148
 ye 101 VFFHRELPLWISASDDQTIKRWVWQSRKEIACLTGHNHVYVCAQFHPPTDD 150

bo 149 LVVSASLDQTVRWVWISGLKKNLSPGAVESDVRGITGVDLFGT..TDAV 196
 ye 151 LVVSASLDQTVRWVWISGLKKNLSPGAVESDVRGITGVDLFGT..TDAV 200

bo 197 VKHVLGHDGRGVNNAAFHPTMPLIVSGADDRQVKIWRMNEKAWVEVDTCR 246
 ye 201 VKFVLEGHTRGVNNAAFHPTMPLIVSGADDRQVKIWRMNEKAWVEVDTCR 250

bo 247 GHYNNVSCAVFHPQELILSNSEDKSIRVWDMSKRTGVQVTFRRDHRDFWY 296
 ye 251 GHTNNVDSVIFHPHQELIISVGEDKTLRVWDLKRTVPVKQFKRENDRFWL 300

bo 297 LAAHENINLEAAGHDGGMIVFKLEREREPAYAVHGNMLHYVDRFLRQLDF 346
 ye 301 IAAPHINLPGAADSGIMVFKLDRERPCSFTHQNLFFVNAEKIQ..SF 349

bo 347 NSSKDVAVMQLRS...GSKFPVF.SMSYNPAENAVLLCTRASLENSTY 391
 ye 350 NFQKRVASLPYASLKGIIQQPDAFRSISYNSPSQHSVLV...NEANGKF 394

bo 392 DLYTIKPKDADTQNPDAPEGKRSGLTAVMVARREAVLDR.MHSLLIKNL 440
 ye 395 ALVILPKQP.VGAVEPTSVTQDGNFATFVGRNRFVYNNKTESVEVRSLL 443

bo 441 KNEITKRVQVFN.CDEIFYAGTGNLLRDAESITLFDVQKRTLASVKIS 489
 ye 444 ENKVTNRKIVVEETVRTIIVAGPGSVLVIHPREVILYDQQKQKVSQLAVK 493

bo 490 KVKYVWISADMSHVALAKHAIIVCNKLEALCNHLENLIVKSGAWDESG 539
 ye 494 NVKYVWISLDGQVVALMSKHTITLAKKLELINSMHETRIKSAAWDESG 543

bo 540 VFIYTTSMHIKYAVTGTGDIYIIRTLDLPIYVTRVKNVYCLDRERPRV 589
 ye 544 VLIYSTLNHIYRSLNDRGIIKTLKERTLYITKVVQKLVYCLNREGEIEI 593

bo 590 LTIIDPTEFKFLALINRKYDEVLMHVRNAKLVGQSIIAYLQKGYPEVAL 639
 ye 594 LTIIDPTEYRFFKALVKNKFEVPLRLIKLNSLVGQNIISYLOKSGYPEIAL 643

bo 640 HFVKDEKTRFSLALECGNIEALEAAKALDDKNCWEKLGEEVALLOGNHOI 689
 ye 644 QFVQDFHIRFDLALAYGNLDVALDEAKKLNDSSTWERLQEAALQAGNASL 693

bo 690 YEMCYQRTKFNKFLSFLYLTIGNLEKLRKMMKIAEIRKDMSGHYONALYL 739
 ye 694 AEMLYQTOHSPDKSFLYLYTIGDNVKNLQKMQNIAQITREDFGSMMLNTPFN 743

bo 740 GDYSERVRIKNCQKSLAYLTAATHGLDEEAESLKE...TFDEPEKRTIIFD 787
 ye 744 NSTKERSSILAEQGSPLAYAVAKANGDEAAAFLEQAEVDEQDVTLPD 793

bo 788 IDENAKLLQPPAPIMPLDNTMPELLTVSKGPFEGSIAKGGKGGALADIDI 837
 ye 794 QMDASNFVQRPIVSKPLE.KWFLKAEALSYPEKAVL..GQIDDLTIDDET 840

bo 838 DIVGTGEGWGEDAELQLDEDFVEATEGLGDDALGKQEGEGGWVDEEDLE 887
 ye 841 PAVNT...TQEQEPELGEENFNDDEGEDEGAWDLGDED...LDVGEELP 884

bo 888 LPPELDIPPGAAGAEDEGFVFPPTKGTSPQIWCNNSQLFVDHILAGSFE 937
 ye 885 EEVEQGEITSPAQVE.....TAIWTNKSLEPAVLVAAGAFD 921

bo 938 TAMRLHDDQVGTQPGPYKQLFLQTYARGRITTYQALEC.LESMYGYPNRN 986
 ye 922 AAVQALSQVGVVVKLEPLKRYFTNIYECRITYIPSTPCELPAQLGVV.RA 970

bo 987 WKDAGLKNQVPAVGLKLNLDLQRLQCYQLTVYKGFEEAVEKFRSILLSV 1036
 ye 971 YDDTVSDEQILPYVPLDVVNEKKNMGYKFNKLNKLDIAIECFREAIYRI 1020

bo 1037 PLLVVDNKQIEAQAQLITICREYIVGLSMETERKLPKETLEQQRICE 1086
 ye 1021 TLLMVDNTEDEKLAHKILETAREYILGLSIELEERSLKE...GNTVRMLE 1067

bo 1087 MAAYFTHSNLQPVHMLVLRALTALNFFKLNFRATAAFARRLLELGPKE 1136
 ye 1068 LAAYFTKAKLSPIHRTNALQVMSQHFHKNFLQASYFAGEFLKI TSSGP 1117

bo 1137 VAQQRKILSACEKNPTDAYQLNVDHNPFDICAAASYRPIYRGKPVKCP 1186
 ye 1118 RAEQARKIKNKADSMASDAIPIDFDPAKFDICAAATYKPTIYEDTPSVSDP 1167

bo 1187 LSGACYSPEFKGQIKVTVTYEIGKDVIGLRIISPQFR 1224
 ye 1168 LTGSKVITEKIDRILAMISKIGAPASGLRIRV... 1201

Figure 5. cDNA-deduced amino acid sequence of bovine α -COP and alignment with its yeast homolog. Sequences determined by Edman degradation are underlined. These sequence data are available from GenBank/EMBL/DBJ under accession number X96768.

Table II. COP-COP Interactions Detected in the Two-Hybrid System

Gal4 DNA-binding domain fusion	Gal4 activating domain fusion	β -Gal activity	Generations/day in -His +25 mM AT
β -COP	δ -COP	74	4.08
δ -COP	β -COP	540	4.80
ζ -COP	γ -COP	812	4.80
γ -COP	ζ -COP	50	1.32
α -COP	ϵ -COP	s.t.*	5.20
ϵ -COP	α -COP	s.t.	2.80
α -COP	β' -COP	s.t.	2.11
—	—	6	0.12
α -COP	—	< 5	< 0.1
β -COP	—	14	1.92
β' -COP	—	< 5	< 0.1
γ -COP	—	12	< 0.1
δ -COP	—	< 5	< 0.1
ϵ -COP	—	< 5	< 0.1
ζ -COP	—	62	1.68
—	α -COP	< 5	< 0.1
—	β -COP	10	< 0.1
—	β' -COP	< 5	< 0.1
—	γ -COP	9	0.24
—	δ -COP	6	< 0.1
—	ϵ -COP	< 5	< 0.1
—	ζ -COP	15	< 0.1
SNF1	SNF4	500	4.30

Quantitative measurement of transcriptional activation of the reporter genes resulting from COP-COP interactions. One unit β -galactosidase activity (reporter gene LacZ) is defined as 1,000 Δ OD405/min mg lysate protein (total). In the right column, the generation times in minimal medium lacking histidine (and containing 25 mM 3-amino 1,2,4-triazole) are given to quantitate the response of the reporter gene HIS3. Except the α/β' -COP interaction, all interactions are shown in both fusion orientations. *s.t., see text.

bodies used for immunoprecipitation. The same holds for the combination of β -COP with γ -COP (not shown).

Discussion

With the cloning and sequencing of the cDNA for δ -COP, the molecular characterization of coatomer, the major cytosolic precursor of the COP I coat, is completed. δ -COP is a stoichiometric component of the coatomer complex, and, like the other COPs, is found in coatomer's soluble state, as well as in the complex when recruited to Golgi membranes, and finally on mature COP I-coated transport vesicles. A complex similar to mammalian coatomer has been identified in yeast (Hosobuchi et al., 1992; Harter et al., 1993; Duden et al., 1994), and direct comparison of peptide structures as obtained by microsequencing and data base searches have revealed a yeast homolog of δ -COP, an open reading frame on chromosome VI that codes for a 60,600-D protein (Murakami et al., 1995). Thus, like the other COPs, δ -COP is strikingly conserved from yeast to mammals. Computer-assisted data base research has revealed an open reading frame in the human genome (ARCN1 gene) as a homolog δ -COP and two proteins that show a faint homology to bovine δ -COP: murine AP 47, a subunit of the Golgi-derived clathrin adaptor complex AP1, which is believed to have kinase activity (Nakayama et al., 1991) and AP50, a subunit of the plasma membrane-derived clathrin adaptor complex AP2, from *S. pombe* (ac-

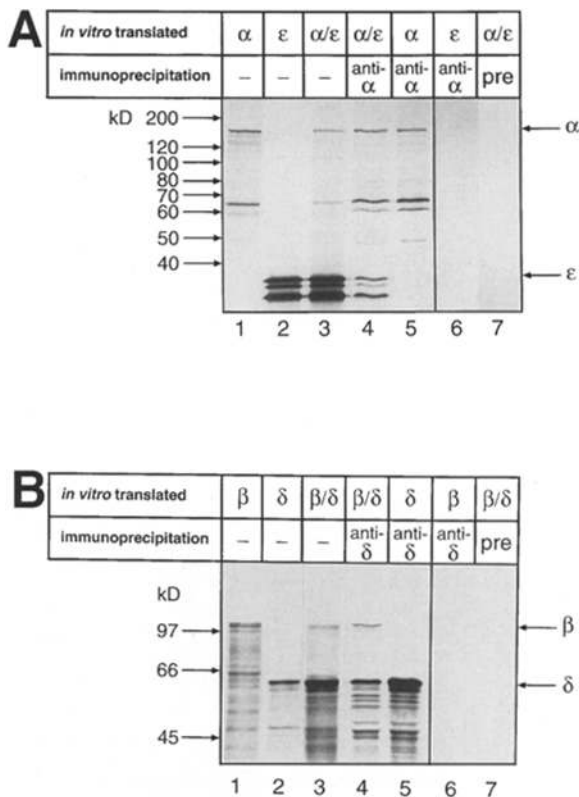


Figure 6. Immunoprecipitation of binary coatomer subcomplexes. (A) Immunoprecipitation of *in vitro* cotranslated α - and ϵ -COPs. ^{35}S -Met-labeled samples were separated by SDS-gel electrophoresis and proteins visualized by autoradiography. The first three lanes show *in vitro* translated α - (lane 1) and ϵ -COP (lane 2) and a cotranslated sample (lane 3). Lanes 4–6 show immunoprecipitations with an anti- α -COP antibody as indicated in the individual lane headings: precipitation from a cotranslated sample (lane 4), of *in vitro* translated α -COP (lane 5), and, as a control, of *in vitro* translated ϵ -COP (lane 6); control precipitation with preimmune serum from a cotranslated sample (lane 7). (B) Immunoprecipitation of *in vitro* translated β - and δ -COPs. *In vitro* translated β - (lane 1) and δ -COP (lane 2) and a cotranslated sample (lane 3); precipitation from a cotranslated sample (lane 4), of *in vitro* translated δ -COP (lane 5), and of β -COP (lane 6); control precipitation with preimmune serum from a cotranslated sample (lane 7).

cession number Q09718). Similar weak homologies were found in two other subunits of mammalian coatomer: β -COP is slightly related to the human β -subunit of AP2 (17% homology over the NH_2 -terminal 450 residues [Duden et al., 1991], and the smallest subunit ζ -COP is reminiscent of both the small subunits of AP1 and AP2 [Kuge et al., 1993]).

We have probed possible protein–protein interactions the individual COPs might exert with each other *in vivo* using the two-hybrid system in yeast. Therefore, we tested mammalian α , β , β' , γ , δ , ϵ , and ζ -COP pair-wise in both possible orientations of fusion proteins. The most striking result of this study was a specific interaction of β -COP with δ -COP, as suggested previously (Lowe and Kreis, 1995). Additionally, these experiments revealed binary interactions of γ - with ζ -COP (confirming earlier findings;

Lowe and Kreis, 1995), of α - with ϵ -COP, and indicate an association of α - with β' -COP. A trimeric complex of α -, β' -, and presumably ϵ -COP has been shown previously (Cosson and Letourneur, 1994; Lowe and Kreis, 1995). Our results suggest that α -COP forms a bridge between β' -COP and ϵ -COP.

The interactions of α - with ϵ -COP and β - with δ -COP were confirmed here biochemically by *in vitro* translation/immunoprecipitation experiments. Remarkably, the binary complex of β - and δ -COP described here was only coimmunoprecipitated in the case β - and δ -COP were synthesized together in the same *in vitro* translation. If each subunit was synthesized separately and these samples mixed and incubated under several conditions, no β -COP was detectable after precipitation with the anti- δ -COP antibody. Additionally, the anti- δ -COP antibody did not immunoprecipitate a complex of *in vitro*-translated β -COP and recombinant His₆-tagged δ -COP overexpressed in *E. coli* (data not shown). These observations indicate that the assembly of these coatomer subunits may depend on cotranslational interactions and/or on accessory proteins that interact cotranslationally. On the other hand, a complex of α - and ϵ -COP was immunoprecipitated by anti- α -COP antibodies if it was either synthesized cotranslationally or formed by mixing the separately translated COPs.

No additional interactions between the individual COPs were revealed by the two-hybrid system, although all COPs were probed, and more than the interactions presented here could be expected. This might be due to the following reasons: while the two-hybrid system is a powerful method to detect protein–protein interactions, its application is limited. One limitation is the fact that it usually reports binary interactions. However, if the binding of a third protein was essential for the association of two proteins in a mammalian cell, this interaction could not be detected with the yeast two-hybrid system. Furthermore, the fact that an interaction is not detectable with the two-hybrid system does not necessarily mean that it does not exist. This may be due to missing posttranslational modifications of the mammalian proteins, which may not occur in the yeast cells (Allen et al., 1995), or simply due to an overall structure of one or both hybrid proteins that does not allow interactions for steric reasons.

Like δ -COP, all deletion mutants of COPs that have been analyzed showed a lethal phenotype (Hosobuchi et al., 1992; Duden et al., 1994; Letourneur et al., 1994; Gerich et al., 1995), a strong indication that it is in fact the complete coatomer complex that is essential in eukaryotic cells. Thus, this quaternary structure is of high functional significance and may turn out to bind various (structurally related) motifs that then might induce functionally different conformations of the protein coat. We propose that the observed interactions of β/δ -COP, γ/ζ -COP, α/ϵ -COP, and α/β' -COP reflect a function in building up and maintaining the complex and presently develop a biochemical system to reversibly dissociate coatomer into subunits and subcomplexes that should enable us to identify the missing interactions leading to the final picture of its architecture.

Plasmids pASI and pACTII, as well as pSE1112 and pSE1111, which contain the fusion products GAL4(1-147)-SNF4 and GAL4(768-881)-SNF1, were generous gifts from Dr. Stephen J. Elledge (Dept. of Biochemistry, Baylor College of Medicine, Houston, TX). The β -COP cDNA was kindly pro-

vided by Dr. T. Kreis. The ϵ - and ζ -COP cDNAs, as well as the cDNAs of ARF and mARF(Q71L), were generous gifts from Dr. J. Rothman. We thank Dr. E. Hurt for providing yeast strain RS453 and for help with the gene disruption experiments. We also thank Dr. I. Haas (Institut für Biochemie I, University of Heidelberg, Heidelberg, Germany) and Dr. E. Hurt (Institut für Biochemie I, University of Heidelberg, Heidelberg, Germany) for critically reading the manuscript.

This work was supported by The Deutsche Forschungsgemeinschaft (SFB 352), the Human Frontier Science Program to L. Orci and F. Wieland, and the Swiss National Science Foundation No. 31-43366.95 (to L. Orci).

Received for publication 15 February 1996 and in revised form 8 July 1996.

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