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Pathway of propionate formation from ethanol in *Pelobacter propionicus*

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Abstract. Whole cells of *Pelobacter propionicus* fermented ($1\text{-}^{13}C$) ethanol and CO_2 to nearly equal amounts of ($2\text{-}^{13}C$) and ($3\text{-}^{13}C$) propionate and to ($1\text{-}^{13}C$) acetate indicating a randomizing pathway of propionate formation. Enzymes involved in the fermentation were assayed in cell-free extracts and cetyltrimethylammonium bromide-permeabilized cells grown with ethanol as sole substrate. Alcohol dehydrogenase, aldehyde dehydrogenase (benzylviologen-reducing), phosphate acetyl transferase, acetate kinase, pyruvate synthase, methylmalonyl CoA: pyruvate transcarboxylase, propionyl CoA: succinate CoA transferase, and the enzymes of the succinate-methylmalonyl CoA pathway all were detected at activities sufficient to be involved in ethanol fermentation. Very low amounts of a b-type cytochrome were detected in ethanol-grown cells (46 nmol · g protein^{-1}). Low cell yields obtained with ethanol as substrate indicate that *P. propionicus* does not conserve energy by electron transport-linked fumarate reduction. Despite the presence of a hydrogenase and a shift in the fermentation of lactate towards the formation of more propionate in the presence of hydrogen, *P. propionicus* was unable to catalyze the reduction of acetate and CO_2 to propionate, unlike *Desulfobulbus propionicus*.

Key words: Propionate formation – Ethanol fermentation – Succinate pathway – *Pelobacter propionicus* – Cytochrome b – Anaerobic electron transport – Pyruvate synthase

Propionate is formed as reduced end product of sugar and lactate fermentation by the Gram-positive *Propionibacterium* spp. and *Arachnia propionica*, as well as some Gram-negative strict anaerobes such as *Selenomonas ruminantium*, *Anaerovibrio lipolytica*, *Veillonella alcalescens*, *Propionispira arboris*, and *Bacteroides fragilis*. All these species use the so-called succinate pathway for propionate formation in which intermediately formed C-4 dicarboxylic acids serve as electron acceptors. Succinate is rearranged via its CoA derivative to methylmalonyl CoA which is decarboxylated and eventually yields propionate (see e.g. Swick and Wood 1960; Allen et al. 1964; Galivan and Allen 1968; de Vries et al. 1977b; Thompson et al. 1984). A few other strict anaerobes such as *Megasphaera elsdenii*, *Bacteroides ruminicola*, and *Clostridium propionicum* (Brockmann and Wood 1975; Leaver et al. 1955; Wallnöfer and Baldwin 1967) form propionate via the acrylate pathway which, contrary to the succinate pathway, does not involve a symmetrical intermediate and, therefore, does not randomize the distribution of selectively labeled carbon atoms. Experiments with propionate labeled in the C-atoms 2 or 3 indicated that also methanogenic degradation of propionate in enrichment cultures, sediments, and sewage sludge employs the succinate pathway (Koch et al. 1983; Schink 1984). Enrichments with ethanol or 2,3-butanediol lately led to the isolation of bacteria which form propionate from C-2 compounds (Samain et al. 1982; Laanbroek et al. 1982; Schink 1984). These findings proved that propionate is not only produced during breakdown of more complex substrates, e.g. sugars, but also by fermentation of C-2 compounds with concomitant reduction of carbon dioxide. One of these bacteria, *Desulfobulbus propionicus*, is a sulfate-reducing bacterium which under hydrogen/carbon dioxide atmosphere forms increased of propionate and less acetate (Laanbroek et al. 1982; Stams et al. 1984). Also some other Gram-negative propionate formers such as *Propionispira arboris* (Schink et al. 1982; Thompson et al. 1984) contain hydrogenases which may attribute an important role as hydrogen sink to these bacteria and to propionate formation in a complex anoxic bacterial community. In the present study, the pathway of propionate formation from ethanol in *Pelobacter propionicus* is elucidated. Special emphasis was laid on the question how the C_3 skeleton is formed from C_2 precursors and to what extent hydrogen affects propionate fermentation by this bacterium.

Materials and methods

Cultivation. Pelobacter propionicus strain Ott Bd 1 (Schink 1984) was grown in a carbonate-buffered sulfide-reduced mineral salts medium as described earlier (Schink and Pfennig 1982; Schink 1984). A similar medium was used for growth of *Desulfobulbus propionicus* strain 1 pr 3. Growth experiments were carried out at 28–30°C in 20 ml glass tubes sealed with rubber-lined screw caps or butyl rubber septa (Bellco, Vineland, USA). Growth was followed by direct turbidity measurement with a Bausch and Lomb Spectronic 70 spectrophotometer at 650 nm wavelength. Larger amounts of cells were grown in screw cap bottles or 10 l bottles sealed with rubber stoppers under N_2/CO_2 (80/20%) atmosphere.

Preparation of cell-free extracts. Cells were harvested at the late logarithmic growth phase by centrifugation, washed

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once with either 100 mM Tris-HCl buffer, pH 7.8, or 50 mM potassium phosphate buffer, pH 7.0, and stored as wet cell paste anaerobically at −20° C. 1 g of wet cell paste was suspended in 2 ml of the respective buffer containing 1 mM dithiothreitol and 2 mM $MgCl_2$. Cell-free extracts were prepared anaerobically under N_2 either by French press treatment at 1450 bar or by ultrasonic disintegration. After removal of cell debris by centrifugation at 10,000 × g for 15 min, the supernatant was stored oxygen-free in a butyl rubber-sealed screw cap tube at 0° C. Some enzyme assays were also carried out with cell suspensions permeabilized with cetyltrimethylammonium bromide (modified after Friedrich et al. 1981). Intact cells (1 – 50 µl of a suspension with 5 – 10 mg protein · ml^{-1}) were transferred by syringes into the anaerobically sealed cuvettes after removal of free oxygen (see below), and 5 – 20 µl of a 0.5% (w/v) aqueous cetyltrimethylammonium bromide solution was added 2 – 5 min before the reaction was started.

Enzyme assays. Enzyme assays were carried out anaerobically at 30° C in 1 ml cuvettes with 1 cm light path. The cuvettes carried Thunberg-type glass tops which allowed addition of the starting reagent by tipping, and were sealed with rubber septa. The reagent mixture was gassed with oxygen-free nitrogen gas for at least 5 min before the cell extract was added. A Perkin Elmer 124 or a Zeiss PM 4 spectrophotometer was used.

Pyruvate synthase (pyruvate benzylviologen oxidoreductase) was assayed with benzyl viologen as electron acceptor in the presence and absence of coenzyme A according to Odom and Peck (1981). Aldehyde dehydrogenase was measured in a similar manner with benzyl viologen as electron acceptor in the presence and absence of coenzyme A. The reaction was started by injecting acetaldehyde from a 100 mM stock solution to 1 mM final concentration into the prereduced reaction mixture. Hydrogenase was assayed with benzyl viologen as described earlier (Schink 1985a). Alcohol dehydrogenase, NAD-dependent lactate dehydrogenase, acetate kinase, and phosphate acetyltransferase were measured by standard procedures (Bergmeyer 1974). NAD-independent lactate dehydrogenase was assayed after Stams and Hansen (1982). Malate dehydrogenase, fumarase, succinate dehydrogenase, and methylmalonyl CoA: pyruvate transcarboxylase were measured according to Stams et al. (1984) Methylmalonly CoA decarboxylase was assayed after Hilpert and Dimroth (1983), propionyl CoA: succinate CoA transferase after Hilpert et al. (1984). Fumarate reductase was measured after Boonstra et al. (1975), pyruvate carboxylase after Scrutton et al. (1969), phosphoenolpyruvate carboxylase after Maeba and Sanwal (1969), phosphoenolpyruvate carboxykinase after Lane et al. (1969), phosphoenolpyruvate carboxytransphosphorylase after Wood et al. (1969), malic enzyme after Hatchikian and LeGall (1970) and succinyl CoA synthetase after both Dijkhuizen et al. (1980) and Bridger et al. (1969). The overall reaction from succinate to propionate was followed in a coupled spectrophotometric assay. The mixture contained 500 µl 50 mM potassium phosphate buffer, pH 7.5; 100 µl 2 mM NADH; 100 µl 50 mM sodium pyruvate; 100 µl 1 mM cobalt chloride; 50 µl 1 mM coenzyme B_{12} (adenosylcobalamin), and 50 µl permeabilized cells. The reaction was started by addition of 100 µl 20 mM succinate in the presence and absence of catalytic amounts of ATP, coenzyme A, or succinyl CoA.

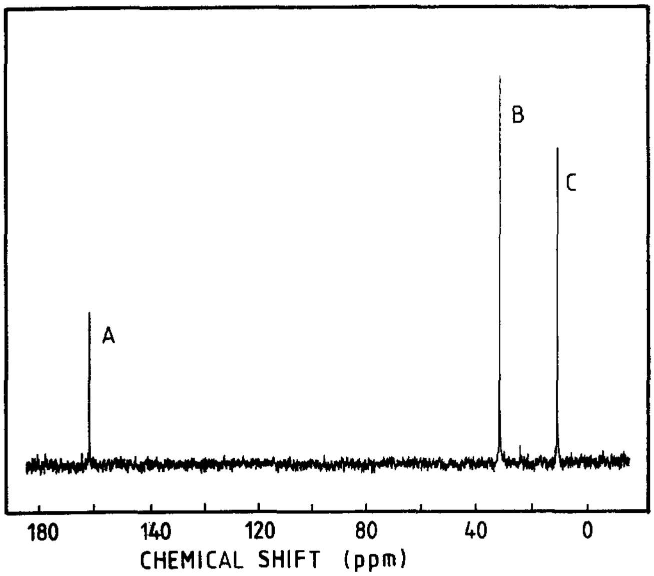

Fig. 1. NMR-spectrum of products formed during growth of *Pelobacter propionicus* with [1-^{13}C] ethanol. *A*: $CH_3^{13}COOH$; *B*: $CH_3^{13}CH_2COOH$; *C*: $^{13}CH_3CH_2COOH$

Cytochromes. Cytochromes were determined in cell-free extracts and membrane preparations obtained by ultracentrifugation (1 h at 120,000 × g). Redox difference spectra were measured in a Shimadzu UV 300 double-beam spectrophotometer; extracts were reduced with dithionite or oxidized by air and ferricyanide. Cytochromes were identified by their typical absorption bands (Dickerson and Timkovich 1975) and cytochrome b was quantified assuming an absorption coefficient of 17.5 $cm^2 \cdot \mu mol^{-1}$ for the α-band (Deeb and Hager 1964).

Fermentation of 1-^{13}C ethanol. P. propionicus was pregrown under N_2/CO_2 (80:20) in two 17 ml screw-cap tubes sealed with butyl rubber septa containing 10 ml medium with 10 mM unlabeled ethanol. (1-^{13}C) ethanol was added to a final concentration of 10 mM. After 1 week of incubation samples were taken, and the supernatant after centrifugation was analyzed. ^{13}C NMR spectra were taken as described earlier (Stams et al. 1984).

Chemical analyses. Alcohols and fatty acids were assayed by gas chromatography as described earlier (Schink and Pfennig 1982). Protein was determined after Kuenen and Veldkamp (1972).

Chemicals. All chemicals used were of anaytical grade and obtained from Merck, Darmstadt, FRG, or Fluka, Neu-Ulm, FRG. Biochemicals and enzymes were purchased from Boehringer, Mannheim, FRG, and Sigma Chemical Co., München, FRG. [1-^{13}C] ethanol was obtained from Merck, Sharp and Dohme Ltd., Canada, through IC Chemicalien, München, FRG.

Results

Fermentation of [1-^{13}C] ethanol

Ethanol is fermented by *Pelobacter propionicus* to acetate and propionate in a 1:2 ratio (Schink 1984). With [1-^{13}C] ethanol, the fermentation led to nearly equal amounts (100:92) of [3-^{13}C] propionate and [2-^{13}C] propionate, together with [1-^{13}C] acetate (Fig. 1). This result indicates that

Table 2. Influence of hydrogen on growth and substrate conversion by *Pelobacter propionicus* and *Desulfobulbus propionicus*

Substrate	Gas phase 80%/20%	Maximum turbidity reached OD_{650}	Products formed[a] (mM)		Ratio propionate
			Acetate	Propionate	acetate formed[b]
A. *Pelobacter propionicus*					
No	N_2/CO_2	0.05	0.57	1.13	–
Acetate 5 mM	N_2/CO_2	0.05	4.68	1.14	–
Acetate 5 mM	H_2/CO_2	0.05	4.81	1.14	–
Ethanol 20 mM	N_2/CO_2	0.19	6.01	11.0	1.82
Ethanol 20 mM	H_2/CO_2	0.18	5.60	11.5	2.06
Lactate 20 mM	N_2/CO_2	0.42	5.35	10.0	1.89
Lactate 20 mM	H_2/CO_2	0.35	3.7	12.5	3.64
B. *Desulfobulbus propionicus*					
No	N_2/CO_2	0.06	0.90	0.90	–
Acetate 5 mM	N_2/CO_2	0.06	5.12	0.94	–
Acetate 5 mM	H_2/CO_2	0.06	1.45	4.50	–
Ethanol 20 mM	N_2/CO_2	0.13	7.0	12.3	1.86
Ethanol 20 mM[c]	H_2/CO_2	0.09	5.7	8.0	–
Lactate 20 mM	N_2/CO_2	0.33	5.5	9.6	1.89
Lactate 20 mM[d]	H_2/CO_2	0.11	0.62	6.8	–

[a] Overall products found in the culture medium after 10 days including the remnant products transferred with the inoculum

[b] Calculated for the net products formed

[c] 7.1 mM ethanol was still left at the end of the experiment

[d] 13.6 mM lactate was still left at the end of the experiment

Experiments were carried out in 20 ml tubes containing 10 ml medium under the atmosphere indicated. Tubes were sealed with butyl rubber septa and incubated lying on a slow shaker. Turbidity was followed over 10 days, and fermentation products were assayed at the end. All numbers given are means of at least 4 independent experiments in every case

acetate and propionate in the same ratio as *Pelobacter* did, however, with lower yields in both cases. Fermentation of ethanol and lactate was strongly inhibited by hydrogen, and the substrate had not been completely utilized after 10 days of incubation. Resting cells of *Desulfobulbus* converted acetate to propionate with hydrogen as electron donor, a reaction not observed with *Pelobacter* cells. This conversion was not associated with growth. Growth and fermentation balances of both bacteria were not influenced by addition of fumarate, neither in the presence nor in the absence of hydrogen or formate.

Discussion

Pathway of propionate formation

The pathway of propionate formation from ethanol by *Pelobacter propionicus* has been elucidated in the present study by ^{13}C-NMR experiments and enzyme assays. The results can be combined into the metabolic scheme presented in Fig. 3. Oxidation of ethanol to acetate proceeds via acetaldehyde, acetyl-CoA, and acetyl phosphate. ATP is formed in the acetate kinase reaction. The electrons released in this oxidative branch of the metabolism are used for the reductive synthesis of propionate. High activities of a benzyl viologen – dependent pyruvate – oxidizing enzyme in ethanol-grown cells indicate the presence of a pyruvate: ferredoxin oxidoreductase (pyruvate synthase), an enzyme able to catalyze the reductive synthesis of pyruvate from acetyl CoA and carbon dioxide. We assume that the electron acceptor of the aldehyde dehydrogenase enzyme, probably a ferredoxin, functions as the electron donor in the pyruvate synthase reaction. This is the first report that pyruvate synthase operates towards pyruvate formation in the dissimilatory metabolism. In clostridia, it functions mainly in pyruvate degradation (Gottschalk 1986), and in many anaerobes growing with acetate as carbon source, it is the main step in formation of a C_3 unit in the assimilatory metabolism. Operation of this enzyme in pyruvate formation in the dissimilatory metabolism creates an energetical problem: The equilibrium of this reaction is far on the side of acetyl CoA and reduced ferredoxin. Even if this enzyme cooperates closely with the exergonic aldehyde ferredoxin oxidoreductase reaction, the overall reaction:

$$\text{acetaldehyde} + CO_2 \rightarrow \text{pyruvate}^- + H^+$$

is still an endergonic reaction ($\Delta G'_0 = +11.3$ kJ; Thauer et al. 1977) which would need to be pulled by a subsequent exergonic reaction. Unfortunately, the following pyruvate carboxylation reaction is again endergonic:

$$\text{pyruvate}^- + CO_2 \rightarrow \text{oxaloacetate}^{2-} + H^+;$$

$\Delta G'_0 = +23.6$ kJ. The organism combines this carboxylation with methylmalonyl CoA decarboxylation in an almost energy-neutral reaction catalyzed by a transcarboxylase. Similar transcarboxylases have been found in the classical propionibacteria (Swick and Wood 1960; Wood 1972), in *Arachnia propionica* (Allen and Linehan 1977) and in *Desulfobulbus propionicus* (Stams et al. 1984). *Pelobacter propionicus* also links succinate activation to succinyl CoA with propionate formation from propionyl CoA in a CoA transferase reaction. Thus, the whole sequence of reactions from pyruvate to propionate is linked in two reaction cycles, and the efficiency of pyruvate removal depends on the efficiency of the operation of the entire reaction sequence following. This concept is of major importance for the energetics of this process (see below).

Due to the observed sensitivity of the transcarboxylase enzyme to freezing and to Tris buffer, we had for long times

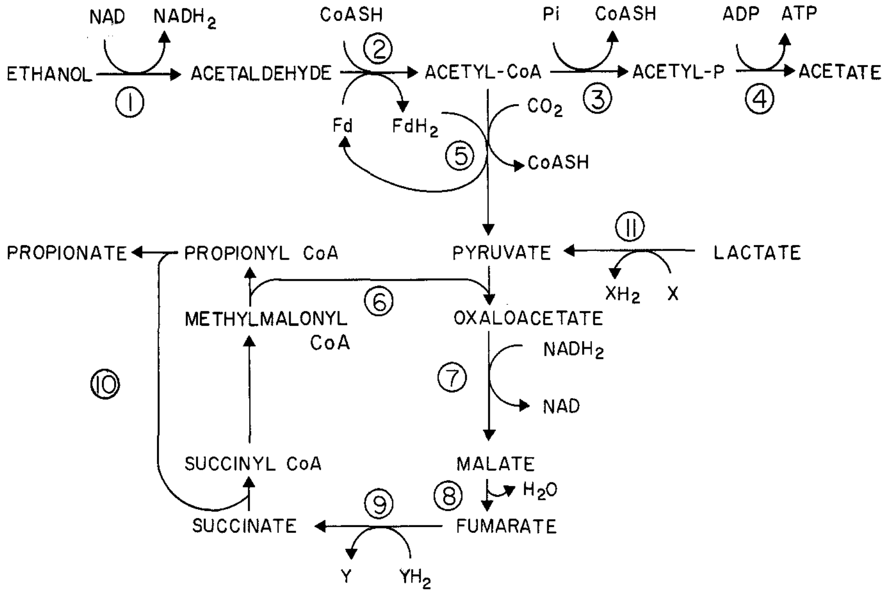

Fig. 3. Pathway of ethanol conversion to propionate by *Pelobacter propionicus*. *Fd*: Unknown low-potential electron carrier, probably ferredoxin; *x*, *y*: hypothetical electron carriers for which dichlorophenol indophenol and reduced benzyl viologen substituted in the present study. *Numbers* in *circles* refer to the following enzymes: *1*: alcohol dehydrogenase; *2*: aldehyde dehydrogenase; *3*: phosphate acetyltransferase; *4*: acetate kinase; *5*: pyruvate synthase; *6*: methylmalonyl CoA: pyruvate transcarboxylase; *7*: malate dehydrogenase; *8*: fumarase; *9*: fumarate reductase; *10*: propionyl CoA:succinate CoA transferase; *11*: lactate dehydrogenase

problems in finding this enzyme and therefore checked for any other C_3 carboxylating enzyme, however, without success. The possibility of involvement of a sodium gradient in the decarboxylation and carboxylation reactions as found with *Veillonella alcalescens* (Hilpert and Dimroth 1983) was also examined in growth experiments with varying additions of sodium chloride and the sodium ionophore monensin, but no indication of sodium participation in the metabolism of *P. propionicus* could be obtained (results not shown). The lack of methylmalonyl CoA decarboxylase in *P. propionicus* explains why this organism cannot grow with C_4-dicarboxylic acids which are the preferred substrated of e.g. *Veillonella alcalescens* (Rogosa 1974).

Presence of a methylmalonyl CoA: succinate CoA transferase in *Pelobacter propionicus* is a major difference in comparison with *Desulfobulbus propionicus* in which both succinyl CoA synthesis and propionate release are ATP or ADP-dependent reactions (Stams et al. 1984). Nonetheless, *Pelobacter* also has phosphate propionyl transferase and propionate kinase when growing with propanol and acetate (Schink 1984); these enzyme activities were detected in cell-free extracts of ethanol-grown cells, too, and are probably by-functions of phosphate acetyl transferase and acetate kinase.

Energetical aspects

Fermentation of ethanol to propionate and acetate is less exergonic than the well-known conversion of lactate to propionate and acetate (calculations after Thauer et al. 1977):

3 lactate $\rightarrow$ 2 propionate$^-$ + acetate + HCO_3^- + H^+
$\Delta G_0' = -55.0$ kJ per mol lactate,

3 ethanol + 2 HCO_3^- $\rightarrow$ 2 propionate$^-$ + acetate$^-$ + H^+ + $3H_2O$
$\Delta G_0' = -41.5$ kJ per mol ethanol.

The free energy changes of the two reactions differ by the free energy of lactate decarboxylation to ethanol (−13.5 kJ per mol). The difference becomes even more pronounced if one takes into account that bicarbonate concentrations are usually in the millimolar range, and has major implications on the fermentation energetics.

The classical propionibacteria as well as *Veillonella alcalescens* ferment lactate to acetate and propionate with concomitant formation of 8.1 to 10.2 g dry cell matter per mol lactate (de Vries et al. 1973, 1977 a, b); this corresponds to the formation of about 1 mol ATP per mol lactate (Stouthamer 1979). It is assumed that per 3 lactate fermented, 1 ATP is formed via acetate kinase and two via cytochrome b-dependent electron transport phosphorylation coupled to fumarate reduction (Stouthamer 1980). Both *Desulfobulbus propionicus* and *Pelobacter propionicus* exhibit by far lower yields when grown with lactate (2.9 and 2.7 g dry matter per mol; Stams et al. 1984; Schink 1984). *Pelobacter* forms even less cell material with ethanol as substrate (1.75 g per mol) and yields of *Desulfobulbus* with ethanol are again lower (0.87 g per mol). Although the higher yields of the classical lactate-fermenting propionibacteria may to some extent be explained by the comparably rich media used in yields assays, it is evident that the two ethanol-fermenting propionate formers *Pelobacter* and *Desulfobulbus* differ from the propionibacteria with respect to the amount of biochemically useful energy that they derive from the fermentation. The very low cytochrome b content of ethanol- and butanediol-grown *Pelobacter* cells suggests that this organism does not conserve energy in the fumarate reductase reaction. Although at first sight this appears to be a loss for the overall fermentation energetics it might well be essential for this organism to pull the pyruvate synthase reaction and thus to allow rapid ethanol utilization. Dispensing with this phosphorylation reaction might help to speed up the whole propionate formation cycle and thus allow rapid ATP synthesis by the acetate kinase reaction. *Desulfobulbus* has by far higher cytochrome contents and is less efficient in ethanol conversion to propionate.

Desulfobulbus and *Pelobacter* differ by their ability to utilize externally provided hydrogen: *Pelobacter* is only slightly influenced by the presence of hydrogen during fermentation of ethanol or lactate and cannot synthetize propionate from acetate, hydrogen and CO_2. *Desulfobulbus* is strongly inhibited hy hydrogen during ethanol or lactate utilization but resting cells convert acetate, hydrogen and

CO_2 to propionate. So far, we do not have an explanation yet for the inhibitory influence of hydrogen on *Desulfobulbus* fermentations. Propionate formation from acetate is an exergonic reaction which should allow ATP synthesis:

$$\text{acetate}^- + HCO_3^- + H^+ + 3H_2 \rightarrow$$
$$\text{propionate}^- + 3H_2O\ \Delta G_0' = -76.8 \text{ kJ per mol.}$$

However, activation of acetate requires at least 1 ATP, and this must be regenerated e.g. by electron transport phosphorylation during fumarate reduction. *Desulfobulbus* catalyzed this reductive conversion of acetate and bicarbonate to propionate which strongly suggests that in the formation of propionate the reduction of fumarate to succinate with hydrogen leads to ATP formation via the fumarate reductase system; this way the process would not consume ATP. An inability of *Pelobacter* to form ATP via the fumarate reductase system in the reduction of fumarate with hydrogen would explain its inability to catalyze the formation of propionate from acetate.

Ecological aspects

Formation of propionate from C_2 compounds is of major importance considering the transformation of fermentation intermediates in anoxic ecosystems. A radiotracer study recently showed that a considerable fraction of intermediately formed ethanol can be transformed to methane and CO_2 through propionate as intermediate, especially in slightly acidic environments (Schink et al. 1985). An earlier study reported formation of propionate together with acetate and butyrate from CO_2 and hydrogen (Goldberg and Cooney 1981), a reaction series that can now be unterstood as a cooperation between homoacetogenic and "homopropionigenic" bacteria of the type of *Desulfobulbus* or *Pelobacter propionicus*. In most – probable – number enumeration experiments with methanol as substrate and freshwater sediments or sewage sludge as inoculum, we often observed traces of propionate formed together with acetate and methane (Schink, unpublished results). At the moment, it cannot be judged with certainty yet to which extent propionate formation can act as hydrogen sink in anoxic environments. Although propionate formation from acetate and CO_2 provides nearly the same amount of energy (–25.6 kJ per mol H_2) as homoacetogenic acetate formation (–26.2 kJ per mol H_2), the yield of utilizable energy for the organism involved is close to zero (see above). Moreover, cleavage of propionate to acetate, CO_2 and H_2 is probably the energetically most difficult step in methanogenic degradation of fermentation intermediates, and seems to take just the same pathway backwards as outlined above for propionate synthesis (Koch et al. 1983; Schink 1985b). It is hard to see the advantage of forming propionate on the one side without significant energy gain, and decomposing it by the backwards reaction with a lot of effort on the other side. Nonetheless, our experiments with hydrogen addition to *D. propionicus* and *P. propionicus* cultures fermenting lactate or ethanol show, similar to the studies with the hydrogenase-positive *Propionispira arboris* (Thompson et al. 1984), that exogenously provided hydrogen can exert a significant influence on the fermentation balance of these propionate-forming bacteria.

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