# Kinetics of Malonyl-CoA Synthetase from *Rhizobium trifolii* and Evidences for Malonyl-AMP Formation as a Reaction Intermediate

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The catalytic mechanism of malonyl-CoA synthetase from *Rhizobium trifolii* was investigated by the steady state kinetics and intermediate identification. Initial velocity studies and the product inhibition studies with AMP and PPi strongly suggested ordered Bi Uni Uni Bi Ping-Pong Ter Ter system as the most probable steady state kinetic mechanism of malonyl-CoA synthetase. Michaelis constants were 0.17± 0.04 μM, 0.24± 0.18 μM and 0.045± 0.026 μM for ATP, malonate and CoA, respectively. The TLC analysis of the $^{32}$P-labelled products in reaction mixture containing [γ-$^{32}$P] ATP in the absence of CoA showed that PPi was produced after the sequential addition of ATP and malonate. Formation of malonyl-AMP, suggested as an intermediate in the kinetically deduced mechanism, was confirmed by the analysis of $^{31}$P-NMR spectra of AMP product isolated from the $^{18}$O transfer experiment using [$^{18}$O]malonate. Two resonances were observed, corresponding to AMP labelled with zero and one atom of $^{18}$O, indicating that one atom of $^{18}$O transferred from [$^{18}$O]malonate to AMP through the formation of malonyl-AMP. Formation of malonyl-AMP was also confirmed through the TLC analysis of reaction mixture containing [α-$^{32}$P]ATP. These results strongly support the ordered Bi Uni Uni Bi Ping-Pong Ter Ter mechanism deduced from the initial velocity and product inhibition studies.

## Introduction

Malonyl-CoA synthetase, which catalyzes the formation of malonyl-CoA directly from malonate and CoA with the hydrolysis of ATP into AMP and PPi, has been purified and characterized from *Rhizobium trifolii* [1]. This enzyme is 63,000 Da monomeric and it shows a high substrate specificity for malonate, ATP, and CoA. Pyridoxal-5'-phosphate, 2,3-butanedione, diethylpyrocarbonate, and N-bromosuccinimide severely inhibit the enzyme, indicating that essential amine, guanidino, imidazole, and indole groups are involved in catalysis[2-4].

Malonyl-CoA synthetase and malonamidases as malonate-specific enzymes were discovered in Rhizobial species[1,5,6]. *Bradyrhizobium japonicum* contain all the malonate-specific enzymes and *R. meliloti* contain only one type of malonamidase, whereas *R. trifolii* contain only malonyl-CoA synthetase. Therefore, it is important to define the enzymatic properties and the physiological role of *R. trifolii* malonyl-CoA synthetase. Recently malonyl-CoA synthetase has been proposed to play a role for the nitrogen flow in symbiosis[1].

Central to the understanding of any enzyme is the knowledge of the kinetic mechanism. Since malonyl-CoA synthetase catalyzes a reaction involving three substrates and three products (Ter Ter reaction), many different catalytic routes can be considered. We report here the results of a kinetic investigation of malonyl-CoA synthetase from *R. trifolii* and the evidences for the formation of malonyl-AMP: enzyme complex during the catalysis.

## Experimentals

**Materials.** ATP, Sodium malonate, CoA, AMP, Dowex 1-X8, Inorganic pyrophosphatase (39 units/mℓ), polyethyleneimine (PEI)-cellulose plates, Hepes were purchased from Sigma Chem. Co.: $H_2{}^{18}O$ (97 atom% enriched) from Aldrich Chem. Co.: [α-$^{32}$P]ATP (−3000 Ci/mmol) and [γ-$^{32}$P]ATP (−3000 Ci/mmol) from Amersham International.

**Preparation of malonyl-CoA synthetase.** Malonyl-CoA synthetase from *Rhizobium trifolii* ATCC 14479 grown on glucose as a carbon source was prepared by the method reported previously[1]. Analysis of the purified enzyme by sodium dodesyl sulfate-polyacrylamide gel electrophoresis revealed that the enzyme was essentially homogeneous.

**Malonyl-CoA synthetase assay.** There are four different assay methods for the determination of malonyl-CoA synthetase activity[7]. Among them the malonohydroxamate assay was used for the preparatioin of the enzyme and $^{18}$O transfer experiment, while the direct spectrophotometric assay, based on the measurement of the increase in absorbance at 232 nm resulting from the formation of a thioester bond of malonyl-CoA ($\varepsilon_{232}=4.5\times10^3$ $M^{-1}$ $cm^{-1}$), was routinely used for kinetic experiments. The standard reaction mixture for direct spectrophotometric assay contained the following components in a final volume of 0.5 mℓ; 100 mM potassium phosphate buffer, pH 7.1; 2 mM sodium malonate; 5 mM $MgCl_2$; 0.1 mM ATP; 0.1 mM CoA, and the enzyme. Reactions were initiated with malonyl-CoA synthetase, and initial rates were obtained from the linear portion of the progress curve. All kinetic measurements were made in cuvettes of 1 cm path length with a Shimazu UV-260 recording spectrometer equipped with a thermo-stated cell compartment. Constant temperature (30℃) was maintained in the cell compartment using a circulating water system.

**Initial velocity experiments.** Because three substrates are involved in the malonyl-CoA synthetase reaction, initial velocity experiments were carried out for the overall reaction in which the concentration of one substrate was varied in the presence of different levels of a second substrate, while the concentration of the third substrate was held

constant at non-saturating concentrations[8]. Under all conditions, the enzyme concentration ensuring linear relationships between incubation time and rates of reaction was chosen. We observed substrate inhibition over 0.6 mM for malonate, 0.3 mM for ATP, and 0.06 mM for CoA. However, the working concentrations of substrates were below their inhibition concentrations. The data reported here were all carried out in duplicate. The concentration of $MgCl_2$ was 5 mM throughout. Because the ATP concentrations utilized in the experiments never exceeded 0.3 mM, we have made the simplifying assumption that this concentration of $MgCl_2$ is sufficiently high that kinetic effects of $Mg^{2+}$ need not be considered.

**Kinetic data analysis.** The kinetic data were analyzed graphically by constructing double reciprocal plots of initial velocities and substrate concentrations, followed by replots of slopes and intercepts against the reciprocal concentrations of changing fixed substrate in the initial velocity studies, or against the inhibitor concentration in the product inhibition studies; All plots and their replots were linear. Kinetic data were fitted to the appropriate initial velocity equation with the FORTRAN programs of Cleland to obtain the desired kinetic parameters[9]. Data from the initial velocity measurements were fitted to Eqs. (1) and (2).

$$v = VAB/(K_aK_b + K_aB + K_bA + AB) \quad (1)$$

$$v = VAB/(K_aB + K_bA + AB) \quad (2)$$

Where $V$ is the maximum velocity; $A$ and $B$ are the concentrations of substrates $A$ and $B$; $K_a$, $K_b$ are $K_m$ constants for the substrates $A$ and $B$, respectively; $K_{ia}$ is dissociation constant for the reaction of $A$ with free enzyme. Because our measurements were made at a single constant value of the fixed substrate, the reported kinetic parameters are apparent values rather than true values.

**Preparation of [$^{18}$O] malonic acid.** [$^{18}$O] Malonate was synthesized by the reaction of malonyl dichloride with $H_2{}^{18}O$. $H_2{}^{18}O$ (0.5 g) and malonyl dichloride (1.3 m*l*) were mixed in a round bottom flask (molar ratio 2 : 1). After one minute, malonic acid remained as a solid product. It was dissolved in 20 m*l* ethylacetate and decolorized with Norit. 20 m*l* benzene was added and the mixture was kept at −20 ℃ for 12 h. [$^{18}$O] Malonic acid was crystallized and dried under reduced pressure, [$^{18}$O] Malonic acid was methylated with ethereal diazomethane and analyzed by GC/MS to be [$^{18}$O] malonic acid containing 50% [$^{18}$O].

**$^{18}$O Transfer experiment.** Reaction mixture contained 100 mM potassium phosphate buffer, pH 7.1, 5 mM $MgCl_2$, 4 mM [$^{18}$O] malonate, 10 mM ATP, 0.5 mM CoA, 200 mM neutralized $NH_2OH$, and 0.06 units of malonyl-CoA synthetase in a total volume of 0.5 m*l*. Reaction was initiated with the enzyme and the mixture was incubated for 1 h at 37℃. The reaction mixture was filtered, using a Centricon-30 ultrafiltration apparatus (Amicon Co.) to remove the protein, and the filtrate was loaded onto a Dowex 1-X8 column (3×2.5 cm). The adenine nucleotides were eluted with a 300 m*l* linear gradient of formic acid (0-5 M). AMP was eluted and its identity confirmed by TLC on PEI-cellulose plate with 0.7 M sodium phosphate buffer, pH 3.5, as a developing solvent. AMP fractions were pooled, lyophilized, and then dissolved in 10 m*l* of distilled water. The pH of the AMP solution was adjusted with diluted NaOH to about pH 8.5 and again lyophilized. The lyophilized AMP was dissolved in 1.3 m*l* of 20 mM Hepes buffer, pH 8.8, containing 1 mM EDTA and 20% $D_2O$. The solution of commercial AMP (11 mM) was prepared in the same condition as above and was used as a standard. The $^{31}$P-NMR measurements of standard and sample AMP were performed as described below.

**NMR measurements.** The $^{31}$P-NMR spectra (121.47 MHz) were obtained in the Fourier-transform mode with a Varian Gemini-300 7.05T spectrometer. NMR measurements were made at 25± 1℃ with a sample volume of 0.8 m*l* contained in a 5 mm tube. A total of 246 transients were accumulated using pulses of 45° (the 90° pulse was 16 μs) and an acquisition time of 3.0 s. A sensitivity enhancement exponential function gave a line broadening of 0.1 Hz. The chemical shifts are reported relative to 85% $H_3PO_4$ as an external reference.

## Results and Discussion

**Initial velocity studies.** Evaluation of the kinetic mechanism and, in particular, the kinetic parameters of an enzyme-catalyzed reaction can often be best approached through the initial velocity studies. Double-reciprocal plots of the initial velocity data allow the differentiation of the kinetic mechanism; ping-pong mechanisms result in one or more parallel lines in double-reciprocal plots, whereas sequential mechanisms exhibit non-parallel lines. The results of an experiment, in which malonate and ATP concentrations were varied at different fixed concentrations of CoA, are presented in double-reciprocal form in Figure 1A and 1B, respectively. In both cases, the lines are parallel. This behaviour is characteristic of the ping-pong mechanism in which one or two products are released before the introduction of a final substrate. It also indicates that CoA is the final substrate introduced[10]. When the initial velocity data of Figure 1A and 1B were plotted with malonate and ATP as the variable substrates, respectively, both sets of results again yielded families of parallel lines, suggesting that the malonate-CoA pair and ATP-CoA pair interaction in the malonyl-CoA synthetase-catalyzed reaction is a ping-pong mechanism. The data fitted well to Eq. (2) and the apparent values for the kinetic constants were summarized in Table 1. There are three classes of ping-pong Ter Ter mechanisms; Bi Uni Uni Bi ping-pong Ter Ter mechanism, Bi Bi Uni Uni ping-pong Ter Ter mechanism, and Hexa Uni ping-pong mechanism. The effects of ATP and malonate concentration changes on the initial rates (at constant non-saturating concentration of CoA) are depicted in Figure 1C. The lines are intersecting, indicating the sequential addition of ATP and malonate (or malonate and ATP) prior to product release. The data fitted well to Eq. (1) and the kinetic parameters are reported in Table 1. From these results, Hexa Uni ping-pong Ter Ter mechanism could be ruled out. In the same experiment as in Figure 1, but with the concentration of CoA, ATP, or malonate each raised 4-fold (a near-saturating concentration), again the same patterns of double-reciprocal plots emerge. Thus, the same patterns of the double-reciprocal plots at constant saturating and non-saturating concentration of each substrate (ATP, malonate, and CoA) suggest that there is no random sequence in malonyl-CoA synthetase-catalyzed reaction.

Taken together, the initial velocity data cited above can

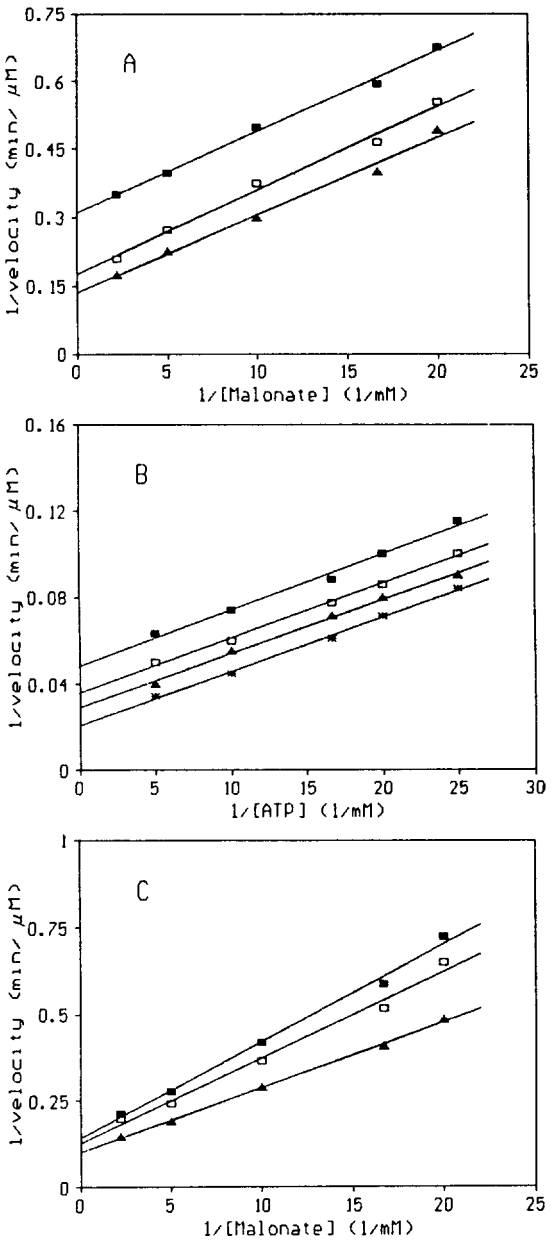



**Figure 1.** Initial velocity patterns on malonyl-CoA synthetase reaction. The reactions were initiated with $3\times10^{-3}$ unit of purified malonyl-CoA synthetase. (A) Plots of 1/v versus 1/[Malonate] at various levels of CoA, and at a constant concentration of ATP (100 μM). CoA concentrations were 10 μM (■), 12.5 μM (□), 25 μM (▲). (B) Plots of 1/v versus 1/[ATP] at various levels of CoA, and at a constant concentration of malonate (0.2 μM). CoA concentrations were 8 μM (■), 12.5 μM (□), 16 μM (▲), 25 μM (*). (C) Double-reciprocal plots of the initial velocity versus malonate concentration at several concentrations of ATP, and a fixed concentration of CoA (25 μM). ATP concentrations were 50 μM (■), 60 μM (□), 100 μM (▲).

be fitted to the rate equation for Bi Uni Uni Bi or Bi Bi Uni Uni ping-pong Ter Ter mechanism. In the absence of product, the initial velocity equation for the two mechanism is the same (Eq. 3).

$$v=VABC/(K_{ia}K_bC+K_cAB+K_bAC+K_aBC+ABC) \quad (3)$$

**Table 1.** Kinetic Constants for Malonyl-CoA Synthetase

| Kinetic constant | App value (mM) |
|---|---|
| $K_{i\ ATP}$ | 0.11 ± 0.02[a] |
| $K_{ATP}$ | 0.037± 0.009[a] |
| | 0.31 ± 0.04[b] |
| $K_{malonate}$ | 0.1 ± 0.02[a] |
| | 0.38 ± 0.18[b] |
| $K_{CoA}$ | 0.045± 0.025[b] |
| | 0.045± 0.006[b] |

[a]Vlue obtained by fitting the data to Eq. (1). [b]Value obtained by fitting the data to Eq. (2).

Where $V$ is the maximum velocity; $A$, $B$, and $C$ are the concentrations of the three substrates; $K_a$, $K_b$, $K_c$ are $K_m$ constants for the substrates $A$, $B$, and $C$, respectively; $K_{ia}$ is the dissociation constant for the reaction of $A$ with free enzyme. The rate equation given in Eq. (3) may be rearranged according to which one of the substrates is fixed to yield Eqs. (4)-(6).

Varying $B$ and $C$ at a constant level of $A$:

$$v=VBC/(K_{ia}K_bC/A+K_cB+K_bC+K_aBC/A+BC) \quad (4)$$

Varying $A$ and $C$ at a constant level of $B$:

$$v=VAC/(K_{ia}K_bC/B+K_cA+K_aAC/B+K_aC+AC) \quad (5)$$

Varying $A$ and $B$ at a constant level of $C$:

$$v=VAC/(K_aK_b+K_cAB/C+K_bA+K_aB+AB) \quad (6)$$

The initial velocity data obtained above were well fitted to these equations (Eqs. 4-6).

**Product inhibition studies.** Although the initial velocity data give a good deal of information for the kinetic mechanism of malonyl-CoA synthetase reaction, our initial velocity data should be supplemented with experiments involving product inhibitors in order to differentiate between Bi Uni Uni Bi and Bi Bi Uni Uni ping-pong Ter Ter mechanisms, and to determine the most likely pathway of substrate addition to the enzyme. The most commonly used method involves holding two substrates at non-saturating concentrations, while varying the third substrate and inhibitor concentrations. The initial velocity data are then plotted in double-reciprocal form, and the inhibition patterns can be used to limit the possible kinetic pathways.

AMP was found to act as an uncompetitive inhibitor of CoA in the malonyl CoA synthetase reaction (Figure 2A). Competitive inhibition was also observed with respect to ATP (Figure 2B). Taken along with the results from the initial velocity experiments, these inhibition patterns indicate that AMP is the $R$ product (final released product) and that substrate $A$ (the first substrate to bind) is ATP and substrate $B$ is malonate[10]. Therefore, Bi Bi Uni Uni ping-pong Ter Ter mechanism is ruled out and Bi Uni Uni Bi mechanism is left as the most reasonable kinetic pathway in malonyl-CoA synthetase reaction. Bi Uni Uni Bi ping-pong Ter Ter mechanism for malonyl-CoA synthetase reaction was further supported by product inhibition with PPi. PPi behaved as a mixed-type inhibitor with respect to malonate (Figure 2C). In the presence of the product, new terms are present in the denominator of the velocity equation (Eq. 7-9).

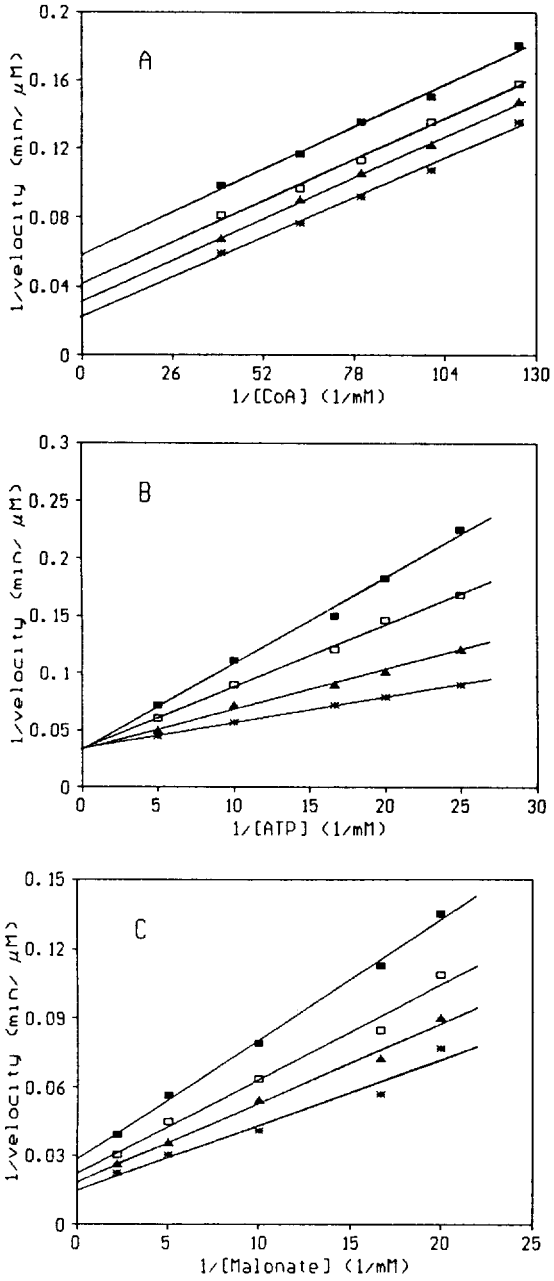



**Figure 2.** Product inhibition patterns on malonyl-CoA synthease reaction. (A) Double-reciprocal plots of the initial velocity versus the CoA concentration at various concentrations of AMP. Malonate and ATP concentrations were fixed at 0.2 mM and 0.1 mM, respectively. AMP concentrations were 100 μM(■), 60 μM(□), and 40 μM (▲); *indicates the initial velocities in the absence of inhibitor. (B) Double-reciprocal plots of the initial velocity versus the ATP concentration at various concentrations of AMP. Malonate and CoA concentration at various concentrations of AMP. Malonate and CoA concentrations were fixed at 0.2 μM and 16 μM, respectively. AMP concentrations were 100 μM (■), 60 μM (□), and 40 μM (▲); *indicates the initial velocities in the absence of inhibitor. (C) Double-reciprocal plots of the initial velocity versus the malonate concentration at various concentrations of PPi. ATP and CoA concentrations were 0.1 mM and 16 μM, respectively. PPi concentrations were 100 μM (■), 60 μM (□), and 20 μM (▲); *is the initial velocity data obtained in the absence of inhibitor.

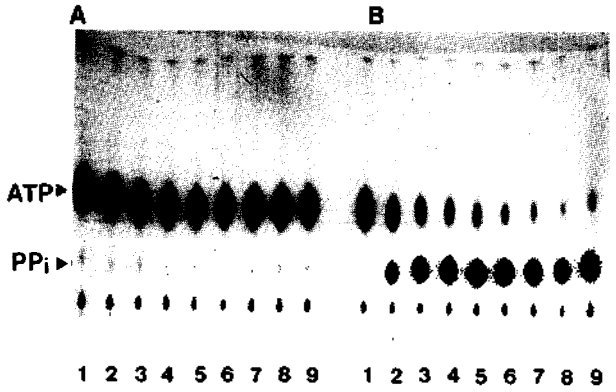



**Figure 3.** Autoradiogram of TLC analysis of the partial reaction products using [γ-$^{32}$P]ATP. The basic reaction mixtures contained 0.1 M potassium phosphate (pH 7.1) buffer, 5 mM $MgCl_2$, 0.2 pmol [γ-$^{32}$P]ATP, and $5\times10^{-3}$ unit of malonyl-CoA synthetase (4.1 pmol) in a total volume of 25 μl. Rections were initiated with the addition of enzyme. The mixture was quickly mixed with a vortex mixer and incubated at 37℃. The aliquots of 1 μl were taken at the indicated time and spotted onto a PEI-cellulose plate. 0.7 M Sodium phosphate (pH 3.5) buffer was used as a developing solvent. (Panel A) without malonate. (Panel B) added malonate to a final concentration of 0.2 mM. Lane 1, control (with boiled enzyme); lane 2, 1 min; lane 3, 3 min; lane 4, 5 min; lane 5, 7 min; lane 6, 9 min; lane 7, 12 min; lane 8, 15 min; lane 9, 20 min. The position of ATP was identified using unlabeled ATP, while the position of Pi and PPi were deduced from the result of pyrophosphatase treatment.

When $C$ is varied in the presence of $R$

$$v=VC/[K_c+C(1+K_a/A+K_b/B+K_{ia}K_b/AB+K_{ia}K_bR/K_{ir}AB+K_aR/K_{ir}A)] \quad (7)$$

When $A$ is varied in the presence of $R$

$$v=VA/[K_a(1+K_{ia}K_b/K_aB+K_{ia}K_bR/K_aK_{ir}B)+A(1+K_b/B+K_c/C)] \quad (8)$$

When $B$ is varied in the presence of $R$

$$v=VB/[K_b(1+K_{ia}/A)(1+K_{ib}K_cP/K_bK_{ip}C)+B(+K_a/A+K_c/C+K_cP/K_{ip}C)] \quad (9)$$

The product inhibition data obtained above were well fitted to the appropriate rate equations (Eqs. 7-9). The apparent values for the inhibition constants obtained from the secondary replots were: AMP has a $K_i$ value of 53.4± 10.0 μM with respect to CoA and of 35.4± 12.1 μM with respect to ATP; PPi has a $K_i$ value of 125± 11 μM with respect to malonate.

**Identification of PPi as the first product.** Since the kinetic analysis shown above suggested that PPi was the first product to be released, the formation of PPi was monitored using [γ-$^{32}$P]ATP in the partial reaction mixture containing no CoA. As shown in Figure 3, PPi was formed after the sequential addition of ATP and malonate. In order to determine the order of ATP and malonate introduced, the isolated of enzyme-ATP (or enzyme-malonate) complex from the partial reaction mixture containing only ATP (or malonate) as a substrate was attempted by gel filtration. But the attempts failed, indicating that ATP or malonate alone may not form a stable complex with the enzyme.

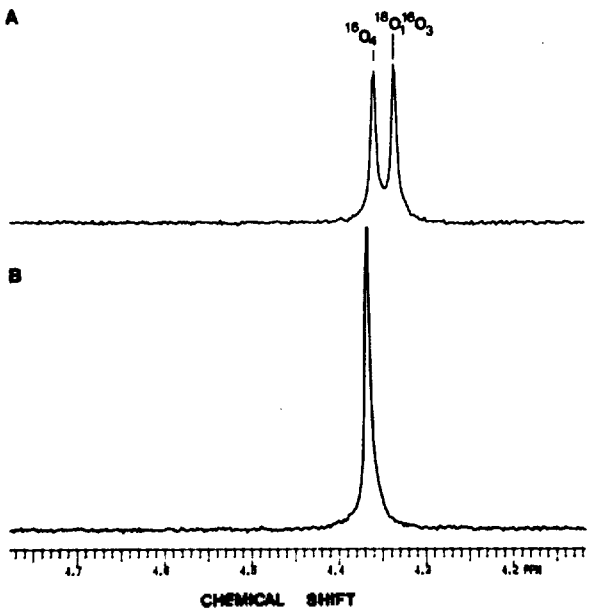



**Figure 4.** $^{31}$P-NMR spectrum of the AMP product of the $^{18}$O transfer experiment. (Panel A) AMP product. The relative integrals of the peaks are 0.96 and 1.00 (Panel B) Standard AMP.

**The evidences for the formation of malonyl-AMP.** From the initial velocity and the product inhibition studies, the formation of malonyl-AMP, an intermediate in the Bi Uni Uni Bi ping-pong mechanism, was suggested. The formation of the intermediate was confirmed by $^{18}$O transfer from [$^{18}$O] malonate to AMP. $^{18}$O-labeled malonate (50% $^{18}$O) was supplied as a substrate together with ATP and CoA in the malonyl-CoA synthetase-catalyzed reaction. The reaction was carried out to 99% completion by the elimination of malonyl-CoA as malonohydroxamate in the presence of $NH_2OH$. AMP, one of the products, was isolated from the reaction mixture by using Dowex 1-X8 anion exchanger. The $^{18}$O content in the AMP was monitored by $^{31}$P-NMR. As shown in Figure 4A, two resonances were observed corresponding to AMP labelled with zero and one atom of $^{18}$O. When unlabelled AMP (used as standard) was added to the sample, the downfield resonance increased in intensity, indicating that this peak was indeed unlabelled AMP (data not shown). The separation between the two resonances was 0.024 ppm, consistent with the chemical shift per $^{18}$O reported by Cohn and Hu[11]. The resonance integrals were almost identical (Figure 4A), indicating that 50% of AMP product was labelled with one atom of $^{18}$O. These results clearly show that malonyl-AMP was formed during the malonyl-CoA synthetase reaction.

The formation of malonyl-AMP was also confirmed by TLC analysis of a reaction mixture containing the enzyme, malonate, and [$\alpha$-$^{32}$P]ATP, which revealed the presence of a novel nucleotide derivative that was neither AMP, ADP, or ATP. Since the malonyl-AMP: enzyme complex may be very unstable in the presence of $Mg^{2+}$, such as in the case of aminoacyl-tRNA synthetase[12-14], we expected that the intensity of the AMP spot would increase with time. However, as shown in Figure 5A, the intensity in the AMP position showed only a temperature increase, concomitant with the appearance of

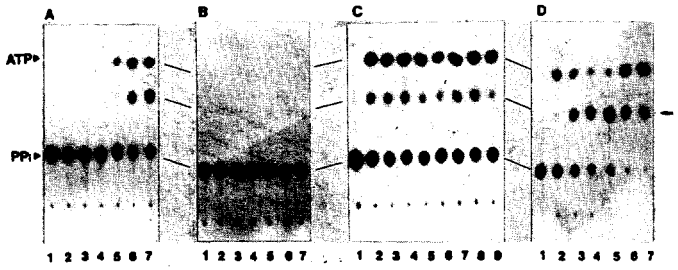



**Figure 5.** Autoradiogram of TLC analysis of reaction products using [$\alpha$-$^{32}$P]ATP. The basic reaction mixtures contained 0.1 M potassium phosphate (pH 7.1) buffer, 5 $\mu$M $MgCl_2$, 0.2 pmol [$\alpha$-$^{32}$P]ATP, other components in the indicated amount, and $7.5\times10^{-3}$ unit of malonyl-CoA synthetase (6 pmol) in a total volume of 25 $\mu l$. All other conditions are as described in the legend of Figure 3. (Panel A) Lane 1, control (with boiled enzyme); lane 2-4, 1 min, 4 min, and 8 min in reaction with only [$\alpha$-$^{32}$P] ATP as a substrate, respectively; lane 5-7, 1 min, 4 min, and 8 min after subsequent addition of malonate to final concentration of 2 mM, respectively. (Panel B) The explanation for each lanes are the same as descried in panel A except for the addition of 2 mM succinate in place of malonate. (Panel C) The basic reaction mixtures were first incubated for 8 min at 37℃. Malonate (final concentration, 2 $\mu$M) and inhibitor (in the indicated concentration) mixed previously were added and the mixtures were quickly mixed with a vortex mixer. The incubation was continued for 8 min at 37℃. Lale 1, control (with boiled enzyme); lane 2, only malonate without inhibitor; lane 3-6, 0.1 $\mu$M, 1 $\mu$M, 10 $\mu$M, and 100 $\mu$M AMP respectively; lane 7-9, 0.2 mM, 2 mM, and 20 mM succinate respectively. (Panel D) The basic reaction mixtures contained [$\alpha$-$^{32}$P]ATP and malonate (final concentration of 1 mM) as substrates. After 4 min, aliquots of 10 $ml$ were taken and mixed with CoA (final concentration of 0.5 mM). The mixture containing CoA was separately incubated and aliquots of 1 $\mu l$ were spotted onto a PEI-cellulose plate at the indicated time. Lane 1, control (with boiled enzyme); lane 2-5, 1 min, 4 min, 8 min, and 12 min from the reaction mixture in the absence of CoA, respectively; lane 6-7, 4 min and 8 min after the addition of CoA, respectively. The positions of each nuleotides were identified using unlabelled ATP, ADP, and AMP. The *arrow* indicates the novel nucleotide derivative, defined as malonyl-AMP.

a new spot. The intensity of the new spot, corresponding to a novel nucleotide derivative, gradually increased with the addition of malonate. However, this spot did not appear with the addition of succinate in place of malonate, indicating that the novel nucleotide derivative was formed from malonate and [$\alpha$-$^{32}$P]ATP (Figure 5B). The transient formation of AMP in the presence of malonate can be explained by the formation of a relatively stable transition-state trigonal bipyramid complex of malonate and ATP. The formation of the novel nucleotide derivative was inhibited by AMP and succinate (Figure 5C). Also, the novel nucleotide derivative disappeared gradually with the addition of CoA, concomitant with the production of AMP (Figure 5D). Combined results of the experiments using [$\alpha$-$^{32}$P]ATP clearly indicate that the novel nucleotide derivative is malonyl-AMP.

**Proposed mechanism of malonyl-CoA synthetase catalysis.** The results from initial velocity and product

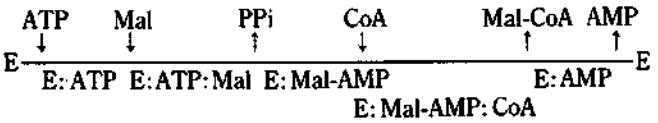
inhibition studies described above support the Bi Uni Uni Bi ping-pong Ter Ter system for malonyl-CoA synthetase reaction. However, it is neceassary to eliminate the possibility of other terreactant ping-pong system, the Theorell-Chance system or the terreactant ping-pong system with rapid equilibrium segment. First, the possibility of Theorell-Chance type case (Bi Uni Uni Bi ping-pong Ter Ter, Theorell-Chance B-P) can be eliminated by looking at the result of product inhibition in which PPi is a mixed-type inhibitor with respect to malonate at unsaturating ATP and CoA concentrations (Figure 2C). Secondly, in the Bi Uni Uni Bi ping-pong Ter Ter system in which the first substrate binds in either direction and the respective complexes that are formed are at equilibrium, the intial velocity equation in the absence of products and the product inhibition patterns is changed differently from the full steady state system.

When $A$ is varied:

$$v = VA/(K_{ia}K_b/B + A(1 + K_b/B + K_c/C)) \quad (10)$$

Compared to the equivalent velocity equation for the full steady-state system, $K_aAB$ term is missing in Eq. (10). Then slope $1/A$ versus $1/B$ replots go through the origin. Secondary replot using the slopes of lines obtained when initial velocity data of Figure 1C were plotted with ATP as variable substrate eliminates the possibility of this system.

As a consequence, we propose that *R. trifolii* malonyl-CoA synthetase catalyzes the reaction in the manner of an ordered Bi Uni Uni Bi ping-pong Ter Ter mechanism as follows:




Where Mal, Mal-AMP, and Mal-CoA represent malonate, malonyl-AMP, and malonyl-CoA, respectively.

This catalytic mechanism is further supported by the isolation of first product, PPi, and by the identification of the key intermediate, malonyl-AMP.

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# Molecular Conformation and Non-Newtonian Viscosity Behavior of Poly(L-proline) in Various Solvent Systems

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The non-Newtonian viscosities (the specific or intrinsic viscosities) of poly (L-proline) (PLP, $M_v$=19,000 and 32,000) in various mixed-solvent systems like water-propanol and acetic acid-propanol of varying compositions were measured during the reverse mutarotation (Form II→Form I) by the application of external pressure (up to 4.5 psi). The non-Newtonian viscosity effect was found to be larger in acetic acid-propanol system than in water-propanol system and to somewhat decrease during the reverse mutarotation at a given solvent system. The non-Newtonian viscosity behavior of PLP in aqueous salt ($CaCl_2$) solution was also studied, from which it was found that the degree of the non-Newtonian effect decreased with increasing salt concentration, and increased with increasing PLP molecular weight. These findings could be explained in terms of conformational changes of PLP in solution (like the helix-helix or helix-coil transition) involved.

## Introduction

Poly(L-proline) (PLP) is known as one of the most interesting biopolymers in that not only it posesses a stable helical structure, despite the lack of the amino proton group, owing to the steric effect of the pyrrolidine rings but it can form