Rat Liver Adenosine Triphosphate: Adenosine Monophosphate Phosphotransferase Activity

I. PURIFICATION AND PHYSICAL AND KINETIC CHARACTERIZATION OF ADENYLATE KINASE III*

(Received for publication, May 13, 1970)

Wayne E. Criss, Virginia Sapico, and Gerald Litwack

From the Fels Research Institute and Department of Biochemistry, Temple University Medical School, Philadelphia, Pennsylvania 19140

SUMMARY

Rat liver adenylate kinase III (ATP:AMP-phosphotransferase, EC 2.7.4.3) has been purified and characterized. The enzyme was purified 1500-fold to a final specific activity of 1000 umoles of ADP produced per min per mg of protein at 25°. The preparation was homogeneous by polyacrylamide gel disc electrophoresis and at 10 mg per ml was essentially a single component by analytical ultracentrifugation.

Molecular weight studies with Sephadex G-150 column chromatography revealed a $V_o : V_r$ ratio of 1.94 which corresponded to a molecular weight of 46,000 for the enzyme. A range of Svedberg values as a function of protein concentration was obtained by ultracentrifugation and established the presence of two molecular weight forms of the enzyme; extrapolation to zero protein concentration indicated two $S_{20,w}$ values of 1.23 and 3.52. With the extrapolated value of the diffusion coefficient of $4.8 \times 10^{-7} \text{ cm}^2 \text{ sec}^{-1}$ and the partial specific volume of 0.74 calculated from the amino acid analysis, molecular weights of 23,000 and 68,000, respectively, were obtained. Frictional and axial ratios were found to be 1.1 and 4.0, respectively. We propose that rat liver adenylate kinase III is a globular protein existing as monomer, dimer, or trimer in very rapid equilibrium.

Amino acid analysis revealed a total of 216 amino acids with a calculated minimum molecular weight of 23,400. The protein was found to be high in glutamic acid, alanine, aspartic acid, and leucine residues; it was low in histidine, methionine, half-cystine, and phenylalanine residues.

Initial velocity studies revealed a narrow specificity for adenine nucleotides. The respective $K_m$ values for ATP, dATP, and dGTP were 0.12, 0.77, and 1.77 mm with respective $V_{max}$ values of 16,000, 40,000, and 25,000 moles of triphosphate min$^{-1}$ mole$^{-1}$ of enzyme. The only monophosphate acceptor, with a $K_m$ of 0.12 mm was 5'AMP. The $K_m$ for ADP was 0.18 mm with a $V_{max}$ of 10,700 moles of diphosphate min$^{-1}$ mole$^{-1}$ of enzyme. It would appear that rat liver adenylate kinase III slightly favors the forward reaction (conversion of ATP).

Nucleotide-transphosphorylating enzymes occur within most forms of life. Many of these enzymes are not specific for the triphosphate moiety, or not specific for the monophosphate moiety or not for both (1-6). The enzyme which is rather more specific for adenine nucleotides is adenylate kinase (ATP:AMP-phosphotransferase, EC 2.7.4.3). Adenylate kinase, which catalyzes the reaction, ATP + AMP = 2 ADP, has been observed in yeast (7, 8) and most mammalian tissues (9-15).

The enzyme has been highly purified from Bakers' yeast (7, 8), rabbit muscle (9), bovine liver mitochondria (11), calf lens (16), and a AgNO$_3$-treated extract of swine liver (18). Numerous similarities and differences can be observed from the reported physical and kinetic data describing experiments with these purified enzymes.

Adenylate kinase activity also may appear in several electrophoretically distinct forms (17-21). Three bands were observed with agarose-acrylamide gel electrophoresis of several rat tissues (19) and four bands were found with isoelectrofocusing of rat liver (21). The four bands separated by isoelectrofocusing were called I, II, III, and IV according to their isoelectric points of pH values 5.9, 7.0, 7.6, and 8.2. In the latter study (21) we reported the loss in hepatomas of the predominant liver isozyme form, adenylate kinase III. This isozyme was also the form which was responsive to diet and hormones. In this communication we report the purification and physical and kinetic characterization of rat liver adenylate kinase III.

EXPERIMENTAL PROCEDURE

Chemicals and Biologicals—Most reagent grade chemicals were purchased from Fisher, Arthur H. Thomas, Mallinckrodt Chemical Works, and Mann. Coupling enzymes (pyruvate kinase, lactate dehydrogenase, hexokinase, glucose-6-P dehydrogenase), and substrates (phosphoenolpyruvate, glucose, NADH, NADP, ADP, AMP, and ATP) were obtained from P-L Biochemicals, Sigma, Boehringer Mannheim, and Worthington. Molecular weight marker proteins used in the data of Fig. 3 were acquired from Sigma and Nutritional Biochemicals. Acrylamide, bisacrylamide, and N$_7$-tetramethylethylenediamine were purchased from Eastman.

Methods—Polyacrylamide gel disc electrophoresis was performed according to the procedure of Criss and McKerns (22). Pharmacia and Scientific Apparatus Glass Company, Philadelphia
phia, Pennsylvania columns were used for column chromatography; the resin was Sephadex from Pharmacia. Protein was determined by the method of Lowry et al. (23). Amino acid analysis was performed with a Phoenix Precision Instruments amino acid analyzer after HCl hydrolysis. A Beckman model DU spectrophotometer with Gilford recorder was used for all kinetic studies. The 440-ml electrofocusing column, and amphi- line carrier ampholytes were purchased from LKB Instruments. Rechromatography was accomplished with ultralfiltration cells obtained from Amicon Corporation, Cambridge, Massachusetts.

Analytical ultracentrifugation was performed with a Beckman model E instrument. Sedimentation coefficients were determined by standard procedures with a double sector standard cell at 60,000 rpm and at 20°C. Photographs were taken at 8- or 16-min intervals. Diffusion constants were determined directly with an artificial boundary cell at 20,000 rpm and at 20°C by determining the slope of a plot of $s^2$ in square centimeters versus $t$ in seconds (24, 25). Photographs were made at 8- or 16-min intervals.

Measurements of distances moved by the maximum ordinate or of $s$ were made with a Nikon two-dimensional microcomparator. Molecular weight values were calculated from the $s^2_{w,v}$ and the $D_{w,v}$ values determined experimentally according to the Svedberg equation.

$$M = \frac{RTS_{w,v}}{D_{w,v}(1 - \varphi)}$$

For this equation a partial specific volume of 0.74 was used which was calculated from the amino acid analysis according to the method of Cohn and Edsall (26).

A frictional ratio, $f_{\text{average}}/f_{\text{minimum}}$, was calculated according to Tanford (27). From the value of the frictional ratio an axial ratio was also determined (27).

**Animals**—CFN male rats were purchased from Carworth Farms, Rockland County, New York. The animals were maintained on lab chow until they were between 200 to 300 g.

**Enzymatic Assays**—Adenylate kinase activity was measured in both directions utilizing coupled enzyme systems. In the forward direction ADP formation was coupled with phosphoenolpyruvate, pyruvate kinase, and lactate dehydrogenase; NADH oxidation was continuously monitored at 340 m$\mu$. In the reverse direction, ATP formation was coupled with glucose, hexokinase, and glucose 6-phosphate dehydrogenase; NADP+ reduction was continuously measured at 340 m$\mu$. Details of these kinetic assays have been previously published (21).

**RESULTS**

**Purification of Adenylate Kinase III**

**Preparation of Cytosol** Rats were fasted 36 hours before killing. The animals were decapitated, exsanguinated, and the livers removed and placed in cold 12.5 mM sucrose-1 mM cysteine. All of the following procedures were performed at 0-5°C. The liver tissue was cooled, blotted, weighed, and homogenized with 2 volumes of cold 12.5 mM sucrose-1 mM cysteine in a Waring blender. The whole homogenate was centrifuged in a Spinco model L ultracentrifuge at 30,000 rpm for 2 hours. The supernatant was used as the cytosol.

**pH Fractionation**—The cytosol was subjected to pH frac-
FIG. 2. Sedimentation velocity experiments of purified adenylate kinase III at 10 mg of protein per ml at 20°. Sedimentation is from left to right. Photographs were made at 8-min intervals starting with the upper left hand photo (zero time) at 56,000 rpm with the AN-D rotor. Solvent is 5 mM phosphate at pH 7.2.

Fig. 3. Sephadex G-150 analysis of adenylate kinase III. Cytosol extracts, marker proteins, or purified adenylate kinase III were placed with blue dextran onto a 250-ml column of Sephadex G-150 equilibrated with 10 mM phosphate buffer at pH 7.4. Elution was made with the phosphate buffer at 25°. The flow rate was 15 ml per hour. Collected were 3-ml fractions, monitored at 280 nm for protein, and assayed for adenylate kinase activity.

combined and concentrated by ultrafiltration with a UM-10 membrane.

Isoelectric Focusing—The concentrated G-75 fraction was applied to an electrofocusing column containing carrier ampholytes of pH 5 to 8. β-Mercaptoethanol or cysteine (1 mM) was added to the column media. The electrofocusing procedure has been described previously (21). At the end of the electrofocusing run, 3-ml fractions were collected and assayed for enzymatic activity. Fractions containing 90% of adenylate kinase III activity were combined and concentrated by ultrafiltration. A UM-10 membrane was used.

Rechromatography on Sephadex G-75—The concentrated electrofocused fraction was dialyzed with 30 volumes of 5 mM sodium phosphate buffer at pH 7.2 in the ultrafiltration cell with a PM-10 membrane. The washed concentrate was layered on a Sephadex G-75 column, 3 × 77 cm, equilibrated in 5 mM sodium phosphate buffer at pH 7.2. The enzyme was eluted with the same buffer and 3-ml fractions were collected and assayed for enzymatic activity. Fractions containing 90% of the adenylate kinase activity were combined and concentrated by ultrafiltration with a UM-10 membrane.

A summary of the purification scheme is given in Table I. The final specific activity was 700 amoles of ADP produced per min per mg of protein at 25°. The overall recovery was 30% with a 1600-fold increase in purification. The last Sephadex step gave little increase in purification, but was necessary to remove ampholytes remaining from electrofocusing and ultrafiltration dialysis.

Enzyme Homogeneity

Polyacrylamide Disc Gel Electrophoresis—Electrophoresis of the purified adenylate kinase III revealed one protein band (Fig. 1) which contained all the adenylate kinase activity on the gel.

Analytical Ultracentrifugation—One peak was observed in the analytical ultracentrifuge when adenylate kinase III was centrifuged at 10 mg per ml (Fig. 2). However, skewing of the slower sedimenting portion of the peak is indicative of a lower molecular weight component as will be discussed below.

Adenylate kinase III appeared to be homogeneous by electrophoresis and essentially one component by ultracentrifugation at lower protein concentrations.

Physical Properties of Adenylate Kinase III

Sephadex G-150 Analysis of Molecular Weight—The molecular weight of adenylate kinase activity from rat liver was studied with liver cytosol extracts from normal, 48-hour fasted, 48-hour fasted-16-hour glucose refed, diabetic, and diabetic-insulin treated rats. All of these procedures caused large changes in vivo
in adenylate kinase activity (21, 29). Partially purified preparations and the final homogeneous preparation were examined in the presence and absence of ATP, ADP, and Mg++. In all studies, the major (>90%) component has a $V_r/V_s$ ratio of 1.94 which corresponded to a molecular weight of 46,000 on a calibrated column (Fig. 3). Infrequently, small but significant amounts of adenylate kinase activity peaks were also observed which corresponded to molecular weights of approximately 21,000 and 160,000. The latter may be caused by nonspecific aggregation.

### Analysis by Ultracentrifugation

A range of Svedberg values was obtained by ultracentrifugation of solutions of 3 to 30 mg per ml of purified adenylate kinase III (Fig. 4). The Svedberg values increased rapidly in the range from 3 to 10 mg per ml and decreased slowly from 10 to 30 mg per ml. Extrapolation to zero protein concentration revealed two $s_{20,w}$ values of 1.23 and 3.52, a condition which is virtually diagnostic of interacting systems involving association-dissociation equilibria with very rapid forward and backward reactions (30). Diffusion coefficients were determined from 10 to 30 mg per ml of purified adenylate kinase (Fig. 5). The slope of the plot of $D_{in,0}$ versus protein concentration was zero. With the $D_{in,0}$ of $4.8 \times 10^{-7}$ cm$^2$ sec$^{-1}$, the molecular weights of 23,000 and 68,000 were calculated for the two Svedberg values (Table II). At a high protein concentration of 30 mg per ml, both the lower as well as the higher forms were visible (Fig. 6). This is taken to confirm the reversible nature of the equilibrium between monomer and polymer. The partial specific volume was calculated from the amino acid analysis to be 0.74 (Table II). The fractional and axial ratios were found to be 1.1 and 4.0, respectively (Table II). It would appear that rat liver adenylate kinase III is a globular protein which exists as a monomer, dimer, or trimer (possibly higher polymers) which are in very rapid equilibrium.

### Amino Acid Analysis

Two separate preparations of purified rat liver adenylate kinase III were used for the amino acid analysis (Table III). Each preparation of 4 mg per ml was hydrolyzed for 48 and 72 hours with 1 volume of 6 N HCl at 110° in sealed glass tubes which had been made anaerobic with N$_2$. Such incubations at 110° for 24 hours yielded incomplete hydrolysis. Calculated from the hydrolysate were 45 dicarboxylic acid and 29 diamino acid (including histidine) residues. This difference in charged groups may contribute to the iso-

---

**Table II**

| Physical properties of adenylate kinase III |
|--------------------------------------------|
| $s_{20,w}$ monomer $\times 10^{18}$ sec$^{-1}$ | 1.2 |
| $s_{20,w}$ trimer $\times 10^{17}$ sec$^{-1}$ | 3.5 |
| $D_{in,0}$ $\times 10^{-7}$ cm$^2$ sec$^{-1}$ | 4.8 |
| Molecular weight |
| Monomer | 23,000 |
| Trimer | 68,000 |
| Column chromatography |
| Dimer | 46,000 |
| Partial specific volume ($\theta$) | 0.74 |
| Frictional ratio ($f_r/f_{min}$) | 1.1 |
| Axial ratio (a:b) | 4.0 |

---

**Fig. 4** (top). Dependence of the sedimentation constant upon concentration of adenylate kinase III protein. Lines were plotted by the least squares procedure.

**Fig. 5** (bottom). Dependence of the value of the diffusion coefficient upon the protein concentration of adenylate kinase III. The least squares line is plotted.

**Fig. 6**. Sedimentation velocity of adenylate kinase III at 30 mg of protein per ml. Direction of sedimentation is from left to right. Photograph was made 112 min after attaining a speed of 60,000 rpm at 30° with a double sector cell and the AN-D rotor. The solvent was 5 mM phosphate, pH 7.2; reference solution was water in this experiment. The main heavier peak is 2.3 S and the lighter shoulder is 0.9 S.
**TABLE III**

**Amino acid composition of adenylate kinase III**

| Amino acids | Moles per 100 g | Residues per 25,000 g | Nearest integral residues per 25,000 g | Residues × mol. wt. |
|-------------|----------------|-----------------------|----------------------------------------|-------------------|
| Aspartic acid | 0.0706 | 20.98 | 21 | 2,793 |
| Threonine   | 0.0640 | 13.59 | 14 | 1,954 |
| Serine      | 0.0307 | 6.89 | 9 | 954 |
| Proline     | 0.0287 | 8.41 | 8 | 920 |
| Glutamic acid | 0.0842 | 23.88 | 24 | 3,528 |
| Glycine     | 0.0692 | 16.31 | 16 | 1,200 |
| Alanine     | 0.0762 | 19.50 | 23 | 2,047 |
| Valine      | 0.0530 | 15.10 | 15 | 1,755 |
| Half-cystine | 0.0118 | 3.60 | 4 | 454 |
| Methionine  | 0.0146 | 3.58 | 4 | 366 |
| Isoleucine  | 0.0476 | 15.48 | 15 | 1,965 |
| Leucine     | 0.0718 | 21.24 | 21 | 2,751 |
| Tyrosine    | 0.0215 | 6.45 | 6 | 1,086 |
| Phenylalanine | 0.0555 | 6.95 | 7 | 1,155 |
| Lysine      | 0.0609 | 17.10 | 17 | 2,402 |
| Histidine   | 0.0108 | 3.47 | 3 | 456 |
| Arginine    | 0.0312 | 9.11 | 9 | 1,566 |
| **Total**   |            | 216 | 27,292 |
| **Minus water hydrolysis** |            |     |     |
| **Total after water hydrolysis** |            | 23,404 |

**TABLE IV**

**Velocity constants for adenylate kinase III**

| Substrate | K<sub>m</sub> (× 10<sup>-4</sup> M) | V<sub>max</sub> (moles substrate min<sup>-1</sup> mole<sup>-1</sup> enzyme) |
|-----------|----------------------------------|---------------------------------------------------------------|
| AMP (at 2 mM) | 0.125 | 16,340 |
| ATP       | 0.770 | 40,850 |
| dGTP      | 1.772 | 25,510 |
| ATP (at 3 mM) | 0.125 | 16,340 |
| AMP       | 0.184 | 10,690 |

At electric point of pH 7.6 for adenylate kinase III (21). A total of 216 amino acid residues were determined which gave a calculated minimum molecular weight of 23,400 (Table III). This was in good agreement with the lower molecular weight of 23,000 which was obtained from analytical ultracentrifugation.

**DISCUSSION**

Rat liver adenylate kinase III has been purified 1500-fold to a final specific activity of 1000 μmoles of ADP produced per min per mg of protein at 25°. The preparation was observed to be homogeneous by polyacrylamide gel disc electrophoresis and was essentially a single component by analytical ultracentrifugation.

Several unique differences are apparent when the physical protein data of the adenylate kinase from bovine liver mitochondria, rabbit muscle, and Bakers' yeast are compared with the rat liver adenylate kinase III (6-11). Diffusion constants are near 10 × 10<sup>-7</sup> cm<sup>2</sup> sec<sup>-1</sup> for the bovine liver mitochondrial and rabbit muscle enzymes, 7 × 10<sup>-7</sup> cm<sup>2</sup> sec<sup>-1</sup> for Bakers' yeast enzyme, and 4.8 × 10<sup>-7</sup> cm<sup>2</sup> sec<sup>-1</sup> for rat liver III enzyme. With Svedberg constants of 2.49, 2.30, 2.96, and both 1.2 and 3.5 for bovine liver mitochondrial, rabbit muscle, Bakers' yeast, and rat liver III enzymes, respectively, the molecular weights were calculated to be 21,500 and 21,000 for the bovine liver mitochondrial and rabbit muscle adenylate kinases, 40,000 for the yeast enzyme, and at the three different weights of 23,000, 46,000, and 68,000 for the rat liver adenylate kinase III. It would appear that all of the purified adenylate kinases have similar minimum molecular weights, but the yeast and rat liver III forms are capable of aggregating at higher protein concentrations. Polymers of the bovine liver mitochondrial enzyme may have been missed since it was examined at protein concentrations (0.4 to 4.0 mg per ml) which were below those required to observe the aggregated forms of the rat liver III enzyme (above 8 mg per ml).

Considerable variations in substrate specificity and Michaelis-Menten constants were observed between the various purified forms of adenylate kinase (6-11). The bovine liver mitochondrial, rabbit muscle, Bakers' yeast, and rat liver III enzymes all used ATP + AMP and ATP + dAMP. The bovine liver mitochondrial adenylate kinase also reacted with GTP + AMP; the yeast enzyme catalyzed reactions between dATP + AMP, GTP + AMP, and ATP + GMP; the rat liver III enzyme also reacted with dGTP + AMP. The forward versus reverse reaction was almost equal with the bovine liver mitochondrial enzyme and the rabbit muscle enzyme. Maximal velocity studies with the yeast enzyme and rat liver III enzyme showed the forward reaction (conversion of ATP) to be favored. Large differences were observed in the apparent K<sub>m</sub> values as K<sub>m</sub> values for all the adenine nucleotides with the bovine liver mitochondrial adenylate kinase were above 1 μM; the K<sub>m</sub> values for the rabbit muscle and rat liver III enzymes were from 0.12 to 0.50 μM; K<sub>m</sub> values for yeast enzyme were from 0.052 to 0.27 μM.

When considered together, the physical data from analytical ultracentrifugation and molecular sieve chromatography indicate a reversible aggregation system for rat liver adenylate kinase III.
On gel columns, the dimer predominates in most cases; whereas during sedimentation the monomer and trimer predominate, the latter accumulating more as the protein concentration increases. In solution, it is suggested that the rates forming the dimer from both monomer and trimer must be small compared to the rates forming monomer and trimer since the dimer was not visualized in ultracentrifugation experiments. On gels, it is conceivable that the monomer is retarded and displaced somewhat from the overall equilibrium. This effect could possibly alter the equilibrium between dimer and trimer favoring accumulation of the former. Alternatively, there may be other factors operative on a solid medium which favor relative concentration of the dimer form of adenylate kinase.

Acknowledgments—We would like to thank Dr. Sidney Weinhouse for his counsel and sincere interest in this work. We also gratefully acknowledge the technical assistance of Emilia Siojo and Lew Vadheim.

REFERENCES
1. MALEY, F., and OCHOA, S., J. Biol. Chem., 233, 1538 (1958).
2. STROMINGER, J. L., HEPEL, L. A., and MAXWELL, E. S., Biochim. Biophys. Acta, 32, 412 (1959).
3. HEPEL, L. A., STROMINGER, J. L., and MAXWELL, E. S., Biochim. Biophys. Acta, 32, 422 (1959).
4. BUCINO, R. J., and ROTH, J. S., Arch. Biochem. Biophys., 132, 49 (1969).
5. HECHT, L. I., POTTER, V. R., and HERBERT, E., Biochim. Biophys. Acta, 15, 134 (1954).
6. NODA, L., in P. D. BOYER, H. LARDY, and K. MYRBACK (Editors), The enzymes, Vol. VI, Academic Press, New York, 1962, Chapter 10, p. 139.
7. CHU, C., SU, S., and RUSSELL, P. J., Biochim. Biophys. Acta, 132, 361 (1967).
8. SU, S., and RUSSELL, P. J., Biochim. Biophys. Acta, 120, 370 (1967).
9. NODA, L., J. Biol. Chem., 235, 237 (1958).
10. NODA, L., and KUBY, S., in S. P. COLOWICK and N. O. KAPLAN (Editors), Methods in enzymology, Vol. VI, Academic Press, New York, 1963, p. 223.
11. Markland, F. S., and CANNON, W. J., J. Biol. Chem., 241, 4124, 4136 (1966).
12. SIEKEVITZ, P., and POTTER, V. R., J. Biol. Chem., 200, 187 (1953).
13. Heldt, H. W., and SCHWALBACH, K., Eur. J. Biochem., 1, 199 (1967).
14. JOHNSTON, C. C., and BARTLETT, P., Biochim. Biophys. Acta, 118, 367 (1967).
15. CHU, C., and PLAUT, W. F., J Biol. Chem., 235, 3290 (1960).
16. KLETHI, J., and MANDER, P., Eur. J. Biochem., 60, 9 (1969).
17. Feldes, R. A., and Harris, H., Nature, 209, 261 (1966).
18. Kotelnikova, A. V., and DOVEDOVA, E. L., Biochim. Biophys. Acta, 34, 584 (1959).
19. HELDT, H. W., and SCHWALBACH, K., Eur. J. Biochem., 1, 199 (1967).
20. BROCHELMANN, W., WOLF, U., and RITTER, H., Humangenetik, 6, 78 (1968).
21. CRISS, W. E., LITWACK, G., MORRIS, H. P., and WEINHOUSE, S., Cancer Res., 30, 370 (1970).
22. CRISS, W. E., and MCKERN, K. W., Biochemistry, 7, 125 (1968).
23. LOWRY, O. H., ROSEBROUGH, N. J., FARR, A. L., and RANDALL, R. J., J. Biol. Chem., 193, 265 (1951).
24. KABAT, E. A., in C. C. THOMAS (Editor), Experimental immunochemistry, Ed. 2, Springfield, Illinois, 1961, p. 678.
25. MOREY, K. A., and LITWACK, G., Biochemistry, 8, 4513 (1969).
26. COHN, E. J., and EDSEL, J. T., Proteins, amino acids, and peptides, Rheinhold Publishing Company, New York, 1943, p. 370.
27. TANFORD, C., Physical chemistry of macromolecules, J. Wiley and Sons, Inc., New York, 1966, p. 556.
28. NODA, L., and KUBY, S. A., J. Biol. Chem., 226, 541, 551 (1957).
29. ADELMAN, R. C., LO, C. H., and WEINHOUSE, S., J. Biol. Chem., 243, 2538 (1968).
30. SCHACHMAN, H. K., Ultracentrifugation in biochemistry, Academic Press, New York, 1959, p. 102.
Rat Liver Adenosine Triphosphate:Adenosine Monophosphate Phosphotransferase Activity: I. PURIFICATION AND PHYSICAL AND KINETIC CHARACTERIZATION OF ADENYLATE KINASE III
Wayne E. Criss, Virginia Sapico and Gerald Litwack

J. Biol. Chem. 1970, 245:6346-6351.

Access the most updated version of this article at http://www.jbc.org/content/245/23/6346

Alerts:
- When this article is cited
- When a correction for this article is posted

Click here to choose from all of JBC's e-mail alerts

This article cites 0 references, 0 of which can be accessed free at http://www.jbc.org/content/245/23/6346.full.html#ref-list-1