1-Glycerol 3-Phosphate Dehydrogenase

I. EFFECTS OF THE SUBSTRATES ON THE CATALYTIC PROPERTIES OF THE HEPATIC NICO-
TINAMIDE ADENINE DINUCLEOTIDE-LINKED ENZYME FROM THE RABBIT*

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SUMMARY

Effects of the substrate on the initial reaction velocity of
nicotinamide adenine dinucleotide-linked 1-glycerol 3-phos-
phate dehydrogenase purified from rabbit liver were studied.

The Michaelis constants for all substrates were determined
in 0.1 M tris(hydroxymethyl)aminomethane-HCl buffer
(pH 7.5) and were found to be 0.68, 0.19, 0.018, and 0.004
mM for L-glycerol 3-phosphate, nicotinamide adenine dinu-
cleotide, dihydroxyacetone phosphate, and reduced nico-
tinamide adenine dinucleotide, respectively. The true
Michaelis constants measured in 0.1 M glycine-NaOH buffer
(pH 10.0) were found to be 0.065 and 0.03 mM for L-glycerol
3-phosphate and nicotinamide adenine dinucleotide, respec-
tively.

High concentration of all four substrates in the reaction
mixture was found to be to some extent inhibitory.

At low concentrations of L-glycerol 3-phosphate or nico-
tinamide adenine dinucleotide, a plot of initial reaction
velocity as a function of L-glycerol 3-phosphate or nico-
tinamide adenine dinucleotide concentration is sigmoidal.

No sigmoidicity is seen in plotting of initial reaction velocity
as a function of either dihydroxyacetone phosphate or reduced
nicotinamide adenine dinucleotide under the conditions used.

However, a plot of initial reaction velocity as a function of
dihydroxyacetone phosphate concentration is sigmoidal in
the presence of L-glycerol 3-phosphate but is not sigmoidal in
the presence of nicotinamide adenine dinucleotide. On the
other hand, a plot of initial reaction velocity as a function of
reduced nicotinamide adenine dinucleotide concentration is
sigmoidal in the presence of nicotinamide adenine dinucleo-
tide but is not sigmoidal in the presence of L-glycerol 3-
phosphate. The results suggest that there are two allo-
steric sites, one for L-glycerol 3-phosphate and the other for
nicotinamide adenine dinucleotide. The binding of L-glyc-
serol 3-phosphate to its allosteric site lowers the Michaelis
constant for L-glycerol 3-phosphate but increases the Mi-
Michaelis constant for dihydroxyacetone phosphate. Similarly,
the binding of nicotinamide adenine dinucleotide to its
allosteric site lowers the Michaelis constant for nicotinamide
adenine dinucleotide but increases the Michaelis constant
for reduced nicotinamide adenine dinucleotide. Interest-
ingly, the binding of L-glycerol 3-phosphate to its allo-
steric site does not change the Michaelis constant for either
nicotinamide adenine dinucleotide or its reduced form. Sim-
ilarly, the binding of nicotinamide adenine dinucleotide to
its allosteric site does not change the Michaelis constant for
either L-glycerol 3-phosphate or dihydroxyacetone phosphate.

On the basis of the present study, it is not clear whether
dihydroxyacetone phosphate or reduced nicotinamide ade-
nine dinucleotide will bind to the allosteric site for L-glycerol
3-phosphate or nicotinamide adenine dinucleotide, respect-
ively.

The work by Meyerhof (1), Green (2), and von Euler et al.
(3, 4) has established that there are two types of glycerol-3-P
dehydrogenases in mammalian systems which are capable of
oxidizing L-glycerol-3-P. Later, Baranowski (5) isolated and
crystallized one of the enzymes, NAD-linked glycerol-3-P
dehydrogenase (L-glycerol 3-phosphate:NAD oxidoreductase
EC 1.1.1.8) from rabbit skeletal muscle. Since then, many
investigators have made a study of this enzyme from rabbit
skeletal muscle (6-10), while a few studies of this enzyme in
other tissues and species have been published (11-14).

No detailed work with respect to the hepatic NAD-linked enzyme
has been published, however. Attempts were, therefore, made
to study in detail the physicochemical and catalytic properties
of this enzyme for a better understanding of physiological
functions of this enzyme and of the significance of the glycerol-3-
P cycle in carbohydrate and lipid metabolism.

This paper presents the effects of the substrate on the catalytic
properties of hepatic NAD-linked enzyme from the rabbit.

EXPERIMENTAL PROCEDURES

Materials—NAD⁺, NADH, glycerol-3-P, and di-n-nonylcylo-
hexylamine salt of dihydroxyacetone phosphate dimethylketal
were purchased from Sigma. The salt of dihydroxyacetone-P
was converted to potassium salt before use. Glycine and
Tris were obtained from Matheson, Coleman and Bell. All
other chemicals used were analytical or reagent grade and obtained from either Mallinckrodt Chemical Works or Fisher Chemical Company. All solutions were prepared with distilled and deionized water.

Animals—White, New Zealand buck rabbits, weighing from 2.5 to 3.2 kg, were purchased from Gopher State Caviary, St.

**Fig. 1 (upper).** Changes in optical density at 340 nm as a function of time. The following conditions were used: $\triangle$—$\triangle$, 0.1 M Tris-HCl buffer (pH 7.5), 0.5 mM NAD$^+$, 0.01 M glycerol-3-P, and 0.05 ml of an enzyme solution in a final volume of 1.0 ml; $\Box$—$\Box$, 0.1 M glycine buffer (pH 10.0), 2.5 mM hydrazine, 0.5 mM NAD$^+$, 10 mM glycerol-3-P, and 0.01 ml of an enzyme solution in a final volume of 1.0 ml; and $\circ$—$\circ$, 0.1 M Tris-HCl buffer (pH 7.5), 0.4 mM dihydroxyacetone-P, 0.1 mM NADH, and 0.01 ml of an enzyme solution in a final volume of 1.0 ml.

**Fig. 2 (lower).** Initial reaction velocity as a function of enzyme concentration. Initial reaction velocity is expressed in terms of millimicromoles of NADH formation or disappearance per min. The experimental conditions are as follows: $\triangle$—$\triangle$, 0.1 M glycine buffer (pH 10.0), 2.5 mM hydrazine (pH 10.0), 10 mM glyceraldehyde-3-P (pH 10.0), and 0.5 mM NAD$^+$ in a final volume of 1.0 ml; $\bullet$—$\bullet$, 0.1 M Tris-HCl buffer (pH 7.5), 10 mM glyceraldehyde-3-P (pH 7.5), and 0.5 mM NAD$^+$ in a final volume of 1.0 ml; $\Box$—$\Box$, 0.1 M Tris-HCl buffer (pH 7.5), 0.8 mM dihydroxyacetone-P, and 0.1 mM NADH. The final pH of the reaction mixture was 7.5, and the final volume was 1.0 ml.

**Fig. 3 (upper).** Plot of reciprocal of initial reaction velocity ($1/V_i$) versus reciprocal of molar concentration of glycerol-3-P. The inset is the plot of initial reaction velocity ($V_i$) in millimicromoles versus molar concentration of glycerol-3-P. The following concentrations of NAD$^+$ were used: 0.06 mM ($\circ$—$\circ$); 0.05 mM ($\Delta$—$\Delta$); 0.04 mM ($\Box$—$\Box$); and 0.02 mM ($\bullet$—$\bullet$). The reaction mixture contained 0.1 M glycine buffer, 2.5 mM hydrazine, a constant amount of enzyme, the indicated amount of NAD$^+$, and glycerol-3-P in a concentration ranging from 0.05 to 0.4 mM. The reaction mixture had a final pH of 10.0 and a final volume of 1.0 ml.

**Fig. 4 (lower).** Plot of reciprocal of initial reaction velocity ($1/V_i$) versus reciprocal of molar concentration of NAD$^+$. The inset is the plot of initial reaction velocity ($V_i$) in millimicromoles per min versus molar concentration of NAD$^+$. The following concentrations of glyceraldehyde-3-P were used: 0.4 mM ($\circ$—$\circ$); 0.2 mM ($\Delta$—$\Delta$); 0.1 mM ($\Box$—$\Box$); and 0.05 mM ($\bullet$—$\bullet$). The reaction mixture contained 0.1 M glycine buffer, 2.5 mM hydrazine, a constant amount of enzyme, the indicated amount of glyceraldehyde-3-P, and NAD$^+$ in a concentration ranging from 0.02 to 0.06 mM. The reaction mixture had a final pH of 10.0 and a final volume of 1.0 ml.
Paul, Minnesota. The rabbits were maintained on Purina rabbit chow and tap water ad libitum until use.

Methods—The concentrations of the substrates, NAD<sup>+</sup>, NADH, glycerol-3-P, or dihydroxyacetone-P, were determined enzymatically based on the fact that at pH 10 the reaction strongly favors glycerol-3-P oxidation and NADH formation and that at pH 7.5 the reaction favors NAD<sup>+</sup> and glycerol-3-P formation. In the presence of one of the substrates at high concentration, the other substrate at low concentration can be determined at pH 10.0 or 7.5. Calculation was made by using 6.22 × 10<sup>3</sup> M<sup>–1</sup> cm<sup>–1</sup> as the molar extinction coefficient of NADH at 340 nm.

The dehydrogenase activity was determined spectrophotometrically by measuring the rate of formation or disappearance of NADH at 340 nm, which was accompanied by the oxidation of glycerol-3-P or the reduction of dihydroxyacetone-P, respectively. A Cary 15 recording spectrophotometer was used to measure the rate of change in absorbance. All measurements were carried out at room temperature. The reaction mixture used for the measurement of the rate of oxidation of glycerol-3-P consisted of 0.1 M glycine-NaOH buffer, 2.5 mM hydrazine, 10 mM glycerol-3-P, 0.5 mM NAD<sup>+</sup>, and a proper amount of enzyme to produce linearity for a period of approximately 45 s (Fig. 1). The final pH and final volume were 10.0 and 1.0 ml, respectively. This procedure was routinely used for the determination of the activity during the purification and for the estimation of unit of an enzyme solution. The rate of oxidation of glycerol-3-P was also measured in 0.1 M Tris-HCl buffer, 10 mM glycerol-3-P, 0.5 mM NAD<sup>+</sup>, and the proper amount of enzyme in 1.0 ml of the reaction mixture at pH 7.5 (Fig. 1). The routine assay mixture for the rate of reduction of dihydroxyacetone-P consisted of 0.1 M Tris-HCl buffer, 0.4 mM dihydroxyacetone-P, 0.1 mM NADH, and proper amount of enzyme to produce linearity for approximately 45 s (Fig. 1). The final pH and final volume were 7.5 and 1.0 ml, respectively.

A 150-fold purified enzyme preparation<sup>1</sup> was used in this study. Concentrated solutions of purified enzyme were usually diluted with 2 mM EDTA (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>-0.1 mM mercaptoethanol (pH 7.5), unless otherwise stated. Under the experimental conditions used, the initial reaction velocity was found to be proportional to the amount of enzyme added to each reaction mixture as shown in Fig. 2.

Biuret reagent was routinely used for the determination of protein concentration, and crystalline bovine serum albumin was used as standard.

RESULTS

Effect of Substrate Concentration on Initial Reaction Velocity—Effects of glycerol-3-P and NAD<sup>+</sup> concentration on initial reaction velocity measured at pH 10.0 were conducted for the purposes of determining the proper substrate concentrations for use during purification and of comparison with the effects at 7.5. A Lineweaver-Burk plot (13) of the reciprocal of the

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1 The detailed purification procedure will be published elsewhere.
Fig. 3. Plot of reciprocal of maximal reaction velocity ($1/V_{\text{max}}$) versus reciprocal of substrate concentration ($1/[S]$) for the oxidation of glycerol-3-P at pH 7.5. $[\text{glycerol-3-P}] \times 10^{-2} \text{M}^{-1}$ or $[\text{NAD}^+] \times 10^{-4} \text{M}^{-1}$ for $[1/S]$. 

Fig. 4. The reciprocal of initial velocity is plotted against reciprocal of NAD$^+$ concentration at several different concentrations of glycerol-3-P. It is clear that the $K_m$ for NAD$^+$ is also dependent upon glycerol-3-P concentration in the reaction mixture. True Michaelis constants for glycerol-3-P and NAD$^+$ at pH 10.0 were obtained by using the method of Florini and Vestling (16) as shown in Fig. 5. It is of interest to note that a plot of initial velocity as a function of NAD$^+$ concentration is not hyperbolic (Fig. 4). No sigmoidicity is seen in plotting of

Fig. 9 (upper). Plot of reciprocal of initial reaction velocity ($1/V_i$) versus reciprocal of molar concentration of dihydroxyacetone-P. The inset is the plot of initial reaction velocity ($V_i$) versus molar concentration of dihydroxyacetone-P. The following concentrations of NADH were used: 0.02 mM ($\triangle$–$\triangle$); 0.015 mM ($\square$–$\square$); 0.01 mM ($\bigcirc$–$\bigcirc$); 0.008 mM ($\blacktriangle$–$\blacktriangle$); and 0.005 mM ($\blacktriangleleft$–$\blacktriangleleft$). The reaction mixture contained 0.1 M Tris-HCl buffer, a constant amount of enzyme, the indicated amount of NADH, and dihydroxyacetone-P in a concentration ranging from 0.1 to 0.225 mM. The reaction mixture had a final pH of 7.5 and a final volume of 1.0 ml.

Fig. 10 (lower). Plot of reciprocal of initial reaction velocity ($1/V_i$) versus reciprocal of molar concentration of NADH. The inset is the plot of initial reaction velocity ($V_i$) versus molar concentration of NADH. The following concentrations of dihydroxyacetone-P were used: 0.25 mM ($\bullet$–$\bullet$); 0.2 mM ($\bigtriangleup$–$\bigtriangleup$); 0.15 mM ($\bigcirc$–$\bigcirc$); 0.125 mM ($\square$–$\square$); and 0.1 mM ($\bigtriangledown$–$\bigtriangledown$). The reaction mixture contained 0.1 M Tris-HCl buffer, a constant amount of enzyme, the indicated amount of dihydroxyacetone-P, and NADH in a concentration ranging from 0.005 to 0.02 mM. The reaction mixture had a final pH of 7.5 and a final volume of 1.0 ml.

Table I

| pH  | Substrate     | NAD$^+$ | Glycerol-3-P | NADH | Dihydroxyacetone-P |
|-----|---------------|---------|--------------|------|-------------------|
| 7.5 | 0.19          | 0.08    | 0.0042       | 0.018|
| 10.0| 0.03          | 0.65    |              |      |
Fig. 12 (upper). Effect of high substrate concentration on the initial velocity. Initial velocity ($V_i$) is expressed in terms of millimicromoles of NADH formation or disappearance per min at various substrate concentrations. The concentration of the second substrate, dihydroxyacetone-P, NADH, or glycerol-3-P was 0.02, 0.05, or 1 mM, respectively. All experiments were carried out in 0.1 M Tris-HCl buffer (pH 7.5).

Fig. 13 (lower). Effect of high glycerol-3-P and NAD$^+$ concentrations on the initial velocity. Initial velocity ($V_i$) is expressed in terms of millimicromoles of NADH formation per min at NAD$^+$ concentration 0.02, 0.05, or 1 mM. All experiments are carried out in 0.1 M Tris-HCl buffer (pH 7.5).

Fig. 14. Inhibition of the rate of reduction of dihydroxyacetone-P by added glycerol-3-P. A, plots following the method of Dixon are shown. Glycerol-3-P is as a varied inhibitor, and dihydroxyacetone-P is as a varied substrate. Each reaction mixture consisted of 0.1 M Tris-HCl buffer (pH 7.5), 0.05 mM NADH, the indicated amounts of glycerol-3-P, dihydroxyacetone-P (0.04 mM, ○—○; 0.02 mM, ●—●), and a constant amount of enzyme in a final volume of 1.0 ml. B, double reciprocal plots of initial reaction velocity ($V_i$) and dihydroxyacetone-P concentration are shown. Each reaction mixture contained 0.1 M Tris-HCl buffer (pH 7.5), 0.05 mM NADH, a constant amount of enzyme, and the indicated amounts of glycerol-3-P and dihydroxyacetone-P in a final volume of 1.0 ml.

Fig. 15. Inhibition of the rate of oxidation of NADH by added NAD$^+$. A, plots following the method of Dixon are shown. Each reaction mixture (1.0 ml) contained 0.1 M Tris-HCl buffer (pH 7.5), 0.4 mM dihydroxyacetone-P, the indicated amount of NAD$^+$, a constant amount of enzyme, and NADH in the concentration of 5 mM (○—○) or 4 mM (■—■). B, double reciprocal plots of initial reaction velocity ($V_i$) and NADH concentration are shown. Each reaction mixture contained 0.1 M Tris-HCl (pH 7.5), 0.4 mM dihydroxyacetone-P, a constant amount of enzyme, the indicated amount of NADH, and different amounts of NAD$^+$ (○—○; none; ■—■, 0.4 mM; △—△, 0.6 mM; ●—●, 0.8 mM) in a final volume of 1.0 ml.

Effect of High Substrate Concentration on Initial Velocity—During the determination of Michaelis constants it was noted that high substrate concentrations elicted an inhibitory effect as shown in Figs. 12 and 13. An additive effect is apparent when both glycerol-3-P and NAD$^+$ are high (Fig. 13). It is possible that the inhibitory effect caused by higher substrate concentration may result from high ionic strength introduced by the addition of the substrates. This possibility was checked and was ruled out, although much higher salt concentration or ionic strength was reported to inhibit a dialyzed liver preparation of the enzyme.

A summary of the true Michaelis constants obtained is presented in Table I.
enzyme preparation of the NAD-linked glycerol-3-P dehydrogenase from rabbit skeletal muscle (17).

**Effect of Product on Initial Reaction Velocity**—The kinetics of the product inhibition was studied for differentiating possible enzymatic reaction mechanisms. Inhibition of the rate of reduction of dihydroxyacetone-P by various amounts of glycerol-3-P is illustrated in Fig. 14. The reduction of dihydroxyacetone-P is inhibited noncompetitively by low glycerol-3-P concentration, whereas a high concentration causes neither competitive nor noncompetitive inhibition according to the method of Dixon (18) (Fig. 14A). Based on the double reciprocal plot, a high glycerol-3-P concentration elicits a mixed type inhibition, and at low concentrations the inhibition is non-competitive (Fig. 14B).

Similar data, as shown in Fig. 15, were obtained with NAD⁺ as an inhibitor of NADH oxidation. NAD⁺ at low concentrations was found to be a noncompetitive inhibitor of the reduction of dihydroxyacetone-P, and at high concentrations it caused a mixed type inhibition with respect to NADH.

Further studies show that a plot of initial reaction velocity as a function of NAD⁺ concentration is sigmoidal in the presence of glycerol-3-P but is not sigmoidal in the presence of NAD⁺ (Fig. 16). NAD⁺ (4 mM) elicits an inhibition which is comparable to that caused by 2 mM glycerol-3-P under the same conditions. Interestingly, no sigmoidicity is seen in the presence of such an amount of NAD⁺. On the other hand, a plot of initial reaction velocity as a function of NAD⁺ concentration is sigmoidal in the presence of 0.8 mM NAD⁺ but is not sigmoidal.

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**Fig. 16.** Inhibition of the rate of reduction of dihydroxyacetone-P by added NAD⁺ or glycerol-3-P. The inset is the plot of the initial reaction velocity (Vi) as a function of dihydroxyacetone-P in the absence or presence of NAD⁺ or glycerol-3-P. Double reciprocal plots of initial reaction velocity (Vi) and dihydroxyacetone-P concentration are shown. Each reaction mixture consisted of 0.1 M Tris-HCl buffer (pH 7.5), 0.01 mM NADH, a constant amount of enzyme, the indicated amount of dihydroxyacetone-P, and in the absence (O—O) or presence of either NAD⁺ (•—•, 1.0 mM; ■—■, 4.0 mM) or glycerol-3-P (□—□, 2 mM).

**Fig. 17.** Inhibition of the rate of oxidation of NADH by added NAD⁺ or glycerol-3-P. The inset is the plots of the initial reaction velocity (Vi) as a function of NADH concentration in the absence (O—O) or presence of either NAD⁺ (□—□, 0.4 mM; ■—■, 0.8 mM) or glycerol-3-P (△—△, 2 mM; ▲—▲, 5 mM). Double reciprocal plots of initial reaction velocity (Vi) and NADH concentration are shown. Each reaction mixture contained 0.1 M Tris-HCl buffer (pH 7.5), 0.4 mM dihydroxyacetone-P, a constant amount of enzyme, the indicated amount of NADH, and either NAD⁺ or glycerol-3-P in a final volume of 1.0 ml.

**Fig. 18 (upper).** Inhibition of the rate of oxidation of glycerol-3-P by dihydroxyacetone-P. Reciprocal of initial reaction velocity (Vi) as a function of dihydroxyacetone-P concentration following the method of Dixon are plotted. Each reaction mixture contained 0.1 M Tris-HCl buffer (pH 7.5), 0.5 mM NAD⁺, a constant amount of enzyme, the indicated amount of dihydroxyacetone-P, and glycerol-3-P (0.25 mM, O—O or 0.5 mM, □—□) in a final volume of 1.0 ml.

**Fig. 19 (lower).** Inhibition of the rate of reduction of NAD⁺ by added NADH. Reciprocal of initial reaction velocity (Vi) as a function of NADH concentration is plotted by the following method of Dixon. Each reaction mixture contained 0.1 M Tris-HCl buffer (pH 7.5), 0.5 mM glycerol-3-P, a constant amount of enzyme, the indicated amount of NADH, and NAD⁺ (O—O, 0.2 mM; □—□, 0.5 mM) in a final volume of 1.0 ml.
in the presence of 5 mM glycerol-3-P which elicits a greater inhibition (Fig. 17). Dihydroxyacetone-P was found to be a competitive inhibitor of glycerol-3-P oxidation with respect to glycerol-3-P (Fig. 18). Likewise, NADH inhibits glycerol-3-P oxidation competitively with respect to NAD+ (Fig. 19). No biphasic slopes are seen in either case which differs from the effects of glycerol-3-P or NAD+ as seen in Fig. 14A or 15B. The inhibition constants \( K_i \) of these compounds were found to be 0.021 mM and 3.5 \( \mu \)M for dihydroxyacetone-P and NADH, respectively. Each inhibition constant is very close to its Michaelis constant when it serves as the substrate, as shown in Table I.

**DISCUSSION**

The catalytic properties of NAD-linked glycerol-3-P dehydrogenase from rabbit skeletal muscle have been studied by quite a number of investigators (8, 19-21). However, no worker has noted that the muscle enzyme is one of the allosteric enzymes. Studies on the nature of catalytic site and structure of the muscle enzyme have also been carried out by several workers (7, 9, 10, 22). On the basis of the present study it is evident that there are some differences in the catalytic properties between the muscle and liver enzyme so far as we have examined. Glycerol-3-P is not only one of the substrates, but also one of the modifiers of the hepatic NAD-linked glycerol-3-P dehydrogenase. Glycerol-3-P acts on the one hand as a positive effector for the oxidation of glycerol-3-P and on the other hand as negative effector of the reduction of dihydroxyacetone-P. Similarly, NAD+ is a positive effector of the reduction of NAD+ and a negative effector of the oxidation of NADH. It is possible that dihydroxyacetone-P or NADH has its own allosteric site which has very high affinity to dihydroxyacetone-P or NADH. The fluorometric methods may be able to answer this question. This possibility will be investigated.

**REFERENCES**

1. MYERHOF, O., Arch. Gesamte Physiol. Menschen Tiere (Pfluegers), 176, 20 (1919).
2. GREEN, D. E., Biochem. J., 30, 629 (1936).
3. VON EULER, H., ADLER, E., GUNTHER, G., AND HELLESTROM, H., Hoppe-Seyler's Z. Physiol. Chem., 246, 217 (1957).
4. VON EULER, H., ADLER, E., AND GUNTHER, G., Hoppe-Seyler's Z. Physiol. Chem., 249, 1 (1957).
5. BARANSKI, T., J. Biol. Chem., 180, 553 (1949).
6. ANKEL, H., BUECHER, T., AND CZOK, R., Biochem. Z., 332, 315 (1960).
7. VAN EYS, J., JUDD, J., FORD, J., AND WOACK, W. B., Biochemistry, 3, 1755 (1964).
8. YEUNO, H. L., AND PAGE, N., Arch. Biochem. Biophys., 76, 105 (1958).
9. FONDY, T. P., ROSS, C. R., AND SOLLHUB, S. J., J. Biol. Chem., 244, 1031 (1969).
10. APITZ-Castro, R., AND SUAREZ, Z., Biochim. Biophys. Acta, 198, 176 (1970).
11. LEHMANN, F. G., AND PFLEIDERER, G., Hoppe-Seyler's Z. Physiol. Chem., 349, 1777 (1968).
12. FONDY, T. P., LEVIN, L., SOLLHUB, S. J., AND ROSS, C. R., J. Biol. Chem., 243, 3148 (1968).
13. CHEN, L.-J., Master's thesis, University of North Dakota, 1965.
14. FINK, S. C., CARTER, G. W., GUTFIELD, S., AND BROWER, W. J., J. Biol. Chem., 245, 6225 (1970).
15. LINWATER, H., AND BURK, D., J. Amer. Chem. Soc., 56, 658 (1934).
16. FLORENS, J. R., AND VESTLING, C. S., Biochim. Biophys. Acta, 20, 575 (1957).
17. SELANDER, O. Z., AND MILLER, O. N., Nature, 135, 859 (1939).
18. DIXON, M., Biochem. J., 55, 170 (1953).
19. BLANCHER, M. C., Can. J. Biochem., 43, 17 (1965).
20. BLACK, W. J., Can. J. Biochem., 44, 1901 (1966).
21. TELEGGI, M., AND KEELETTI, T., Acta Biochim. Biophys. Acad. Sci. Hung., 3, 131 (1968).
22. ANDERSON, B. M., KIM, S. J., AND WANG, C.-N., Arch. Biochem. Biophys., 138, 66 (1970).
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