Investingation of the Reaction of Metal-Nitrosyl Complexes. I. New Nitrosolysis Reaction of Cycloalkanones Using Sodium Pentacyanonitrosylferrate(II)†

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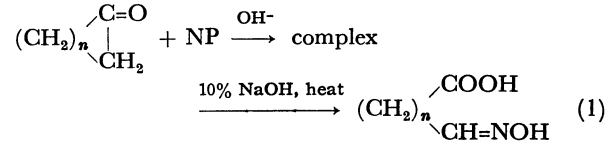
Cycloalkanones reacted with sodium pentacyanonitrosylferrate(II) (NP) to give red-brown or red-violet colored complexes under an alkaline condition. The solvolysis of the complexes gave ω-(hydroxyimino)alkanoic acids under a hot alkaline condition and gave ω-cyanoalkanoic acids or their esters in an acidic condition in good yields. These Products correspond to nitrosolysis products of cycloalkanones. The reaction mechanism was invesigated by use of ^{15}N labeled NP. The complex was formed initially by an electrophilic attack of the nitrosyl ligand of NP to the active methylene of the cycloalkanone. Then a C–C bond cleavage of the resulting ligand, 2-(hydroxyimino)cycloalkanone, occurred by an action of the solvent species under the influence of the central ferrate ion. The solvolysis of the ligand occurred through Beckmann fission by an action of the acid in the coordination sphere.

There have been a number of investigations of the nitrosation of aliphatic and alicyclic ketones by use of alkyl nitrite. While the nitrosation of aliphatic open chain ketones gave mononitrosation products,[1] cyclopentanone, cyclohexanone, and cycloheptanone gave the corresponding α,α′-bis(hydroxyimino) cyclic ketones.[1,2] A reaction of another type, the nitrosolysis reaction: a carbon–carbon bond cleavage through solvolytic nitrosation, was reported for the nitrosation of cycloalkanones by use of nitrosyl chloride.

Kataoka and Ohno[3] found that the nitrosolysis of cyclohexanone under the following conditions gave 5-cyanovaleric acid in 60% yield. The reaction was carried out by use of an ethereal solution of nitrosyl chloride in the presence of sulfuric acid and *N,N*-dimethylformamide under a chilled condition (−30 °C). Recently, Rogic *et al.*[4] reported a novel single step nitrosolysis of cyclopentanone, cyclohexanone, alkylcyclohexanone, cyclododecanone, and cyclotridecanone. The reaction was carried out in liquid sulfur dioxide by use of nitrosyl chloride in the presence of an alcohol. The nitrosolysis of the cycloalkanones under the above conditions gave corresponding ω-(hydroxyimino)alkanoic esters in max 95% yield.

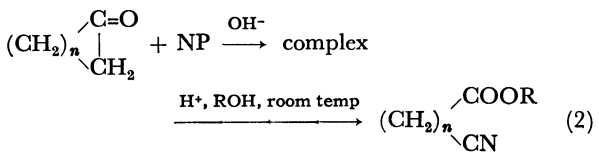
We have been investigating the nitrosation of ketones by using sodium pentacyanonitrosylferrate(II), (sodium nitroprusside) NP, as a nitrosation reagent. In an earlier work[5] prior to these reports, we reported a similar nitrosolysis reaction which occurred in the alkaline hydrolysis of cycloalkanone–NP complexes.



(1)

The complexes reacted in a hot alkaline medium to give ω-(hydroxyimino)alkanoic acids in good yield (Eq. 1).

The present paper deals with the other nitrosolysis reaction of the cycloalkanone–NP complexes under acid-catalyzed conditions: the complexes reacted with solvent species to give ω-cyanoalkanoic acids and their esters also in good yields (Eq. 2).



(2)

The role of nitrosyl ligand of NP in the reaction is discussed in the following section, based on the experimental results using ^{15}N labeled NP. The structure of the intermediate complex is also discussed, based on the information about the structural investigation of an isolated cyclododecanone–NP complex.

Results and Discussion

The Alkaline Hydrolysis Products of the Cycloalkanone–NP Complex. The red-violet or brown colored complexes prepared from NP and cycloalkanones were treated with aqueous alkali at the boiling point. The alkaline hydrolysis products of the cycloalkanone–NP complexes are shown in Table 1. These products were ω-(hydroxyimino)alkanoic acids; however, no 2-(hydroxyimino)-cycloalkanones were found in the hydrolysates. The detailed experimental results have already been described in the previous paper.[5]

The Acid Hydrolysis Products of Cycloalkanone–NP Complex. After the aqueous methanolic solutions of cycloalkanone–NP complexes had been allowed to stand under an acidic condition, other products were found in the solution. These products were ω-cyanoalkanoic acid and their methyl esters (Table 2), which revealed an IR absorption band characteristic of aliphatic nitriles at 2245 cm^{-1}. The NMR data and C, H, N, contents of *p*-bromophenacyl esters derived

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Table 1. Alkaline hydrolysis products of cycloalkanone–NP complexes

Cycloalkanone	Reaction product	Yield (%)	Mp[a] (°C)	Recovery of ketone (%)
Cyclopentanone	$HON{=}CH(CH_2)_3COOH$	38	105—107	60.0
Cyclohexanone	$HON{=}CH(CH_2)_4COOH$	50	112—113	47.5
Cycloheptanone	$HON{=}CH(CH_2)_5COOH$	25	80—83	70.2
4-Methylcyclohexanone	$HON{=}CHCH_2CH(CH_3)(CH_2)_2COOH$	40	68—70	58.0

a) Recrystallized from methyl acetate.

Table 2. Acid hydrolysis products of cycloalkanone–NP complexes

Cycloalkanone	Reaction products	Yield[a] (%)	Bp (3 Torr) (°C)	Mp (°C)
Cyclopentanone	$NC(CH_2)_3COOCH_3$	23.6	66—70	—
	$NC(CH_2)_3COOH$	5.0	110—115	—
	glutarimide	8.9	120—135	149.8
Cyclohexanone	$NC(CH_2)_4COOCH_3$	17.8	88—93	—
	$NC(CH_2)_4COOH$	27.8	133—137	<5
Cycloheptanone	$NC(CH_2)_5COOCH_3$	0.7	95—98	—
	$NC(CH_2)_5COOH$	25.6	140—145	<20
Cyclooctanone	$NC(CH_2)_6COOCH_3$	trace	120	—
	$NC(CH_2)_6COOH$	45.2	146—151	35.5
Cyclododecanone	$NC(CH_2)_{10}COOH$	37.9	185—190	53.5

a) About 40% cycloalkanones were recovered in each experiment.

Table 3. NMR spectral data of some products (δ ppm)

Product	CH_2	$COOCH_3$	Solvent
$NC(CH_2)_3COOCH_3$	1.94 (2H, m), 2.42 (4H, t)	3.62 (3H, s)	CCl_4
Glutarimide	2.00 (2H, m), 2.60 (4H, t)	—	$CDCl_3$
$NC(CH_2)_4COOCH_3$	1.65 (4H, m), 2.37 (4H, t)	3.69 (3H, s)	$CDCl_3$
$NC(CH_2)_4COOH$	1.65 (4H, m), 2.40 (4H, t)	—	$CDCl_3$
$NC(CH_2)_5COOCH_3$	1.60 (6H, m), 2.30 (4H, t)	3.60 (3H, s)	CCl_4
$NC(CH_2)_5COOH$	1.65 (6H, m), 2.34 (4H, t)	—	CCl_4
$NC(CH_2)COOH$	1.6—1.7 (8H, m), 2.35 (4H, t)	—	CCl_4

Table 4. C, H, N contents of *p*-bromophenacyl esters of the products

p-Bromophenacyl ester	Mp (°C)	Formula	Found			Calcd		
			C%	H%	N%	C%	H%	N%
4-Cyanobutyrate	70.5	$C_{13}H_{12}NBrO_3$	50.31	3.87	4.40	50.34	3.90	4.51
5-Cyanovalerate	78.6	$C_{14}H_{14}NBrO_3$	51.66	4.34	4.22	51.87	4.35	4.32
6-Cyanohexanoate	95.4	$C_{15}H_{16}NBrO_3$	53.19	4.61	3.98	53.27	4.77	4.13
7-Cyanoheptanoate	68.3	$C_{16}H_{18}NBrO_3$	54.28	5.21	4.00	54.56	5.15	3.98
11-Cyanoundecanoate	68.2	$C_{20}H_{26}NBrO_3$	58.20	6.49	3.12	58.85	6.42	3.43

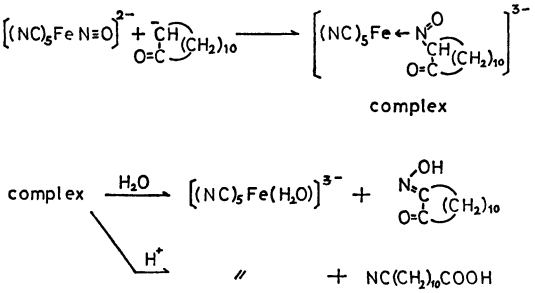

Fig. 1. A possible structure of the cyclododecanone–NP complex and reaction products from it.

from the acids are shown in Tables 3 and 4. No components other than these products were found, except for the products from cyclopentanone–NP complex: this complex gave a by-product, glutarimide.

Structural Investigation on the Cyclododecanone–NP Complex. Hydrolysis of cyclododecanone–NP complex normally gave 12-(hydroxyimino)dodecanoic acid under the alkaline conditions, and gave 11-cyanoundecanoic acid under the acidic conditions. However, after the aqueous solution of the complex had been allowed to stand under a weakly alkaline condition, another crystalline product, 2-(hydroxyimino)cyclododecanone,

was formed. These facts suggest the possible reaction routes which are illustrated in Fig. 1.

To investigate the structure of the intermediate complex shown in Fig. 1, we tried to isolate the cyclododecanone–NP complex in a pure form. The spectral data of the isolated complex supported the predicted structure of the complex illustrated in Fig. 1. As we would expect, hydrolysis of the isolated complex gave under the weakly alkaline conditions 2-(hydroxyimino)-cyclododecanone, and also gave 11-cyanoundecanoic acid under the acidic conditions.

*Investigation of the Reaction Products Prepared from Cyclohexanone and ^{15}N Labeled NP(N*P).* In the hydrolysis of the cycloalkanone–NP complexes, we assumed that the nitrogen atom in the hydroxyimino or cyano group of the reaction products must be introduced from the nitrosyl ligand of NP. To confirm the assumption we have investigated the reaction products prepared from cyclohexanone and N*P, which contained ^{15}N labeled nitrosyl ligands.

Three kinds of N*P (N*P-0, N*P-5 and N*P-30) were prepared from sodium hexacyanoferrate(II) and ^{15}N labeled sodium nitrites. These sodium nitrites contained ^{15}N of natural abundance, 5%, and 30%. The IR spectra of the prepared N*P revealed the characteristic bands at 2150 cm^{-1} (ν CN), 1945 cm^{-1} (ν ^{14}NO), and 1915 cm^{-1} (ν ^{15}NO, calcd 1911 cm^{-1}). The intensity of the last band increased with an increase in the ^{15}N content of N*P, as shown in Fig. 2.

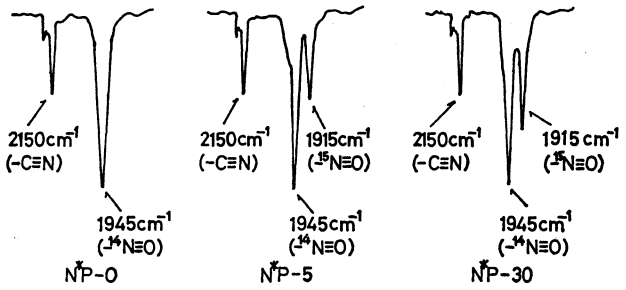

Fig. 2. IR spectra of N*P.

After having been prepared from cyclohexanone and N*P under the hot alkaline condition (Eq. 1), 6-(hydroxyimino)valeric acid was checked for the presence of the hydroxyimino-^{15}N group. Although the hydroxyimino-^{15}N group was difficult to characterize by IR spectral analysis, the presence of ^{15}N labeled fragment ion peaks (*m/e* 73, 128, and other values) in the mass spectra indicated the presence of the hydroxyimino-^{15}N group, as shown in Eq. 3. The relative abundance of the labeled ion peaks increased with an increase in the ^{15}N content of N*P, as shown in Table 5.

$$\begin{array}{l}[HO\text{–}^{15}N{=}CH(CH_2)_4COOH]^{\ddagger} \longrightarrow M^{\ddagger}\text{–}H_2O \quad m/e\ 128 \\ \quad M^+\ m/e\ 146 \qquad\qquad \searrow\ CH_2\text{–}CH_2 \\ \qquad\qquad\qquad\qquad\quad HO\text{–}{}^{15}\overset{+}{N}{=}CH \quad m/e\ 73\end{array} \tag{3}$$

A more reliable method for detecting the hydroxyimino-^{15}N group was performed by means of the following procedure. Methyl 5-cyanovalerate prepared from the 6-(hydroxyimino)valeric-^{15}N acid by an ordinary method (Eq. 4) was checked for the presence of the cyano-^{15}N group.

Table 5. Ratios of relative abundance of the fragment ions(I)

N*P	*m/e*73/*m/e*72	*m/e*128/*m/e*127
N*P-0	47%	25%
N*P-5	49	27
N*P-30	78	65

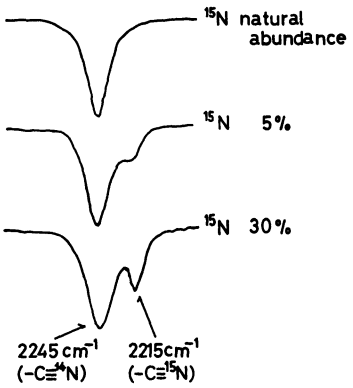

Fig. 3. IR spectra of the methyl 5-cyanovalerates-^{15}N prepared from cyclohexanone and N*P.

$$HO\text{–}{}^{15}N{=}CH(CH_2)_4COOH \xrightarrow{Ac_2O} {}^{15}NC(CH_2)_4COOH \xrightarrow{CH_3OH,\ H^+} {}^{15}NC(CH_2)_4COOCH_3 \tag{4}$$

The IR spectrum of the methyl 5-cyanovalerate-^{15}N revealed the characteristic bands at 2245 cm^{-1} (ν ^{14}NC) and 2215 cm^{-1} ($\nu^{15}NC$, calcd 2210 cm^{-1}). The intensity of the latter absorption band definitely increased with an increase in the ^{15}N content of N*P used for the preparation of 6-(hydroxyimino)valeric-^{15}N acid, as shown in Fig. 3.

The mass spectrum of the methyl 5-cyanovalerate-^{15}N of course revealed ^{15}N labeled fragment ion peaks at *m/e* 83, 111, and other values.

$$\begin{array}{l}[{}^{15}NC(CH_2)_4COOCH_3]^{\ddagger} \longrightarrow {}^{15}NC(CH_2)_4C{=}O^+ \quad m/e\ 111 \\ \quad m/e\ 142 \qquad\qquad \downarrow \\ \qquad\qquad\qquad\qquad {}^{15}NC(CH_2)_4{}^+ \quad m/e\ 83\end{array} \tag{5}$$

The relative abundance of the labeled ion peaks also increased with an increase in the ^{15}N content of N*P used. The ratios of the relative abundance of the labeled and the corresponding unlabeled ion peaks were in fair agreement with the calculated values, as shown in Table 6.

The methyl 5-cyanovalerate-^{15}N were directly prepar-

Table 6. Ratios of relative abundance of the fragment ions(II)

N*P	*m/e* 83/*m/e* 82		*m/e* 111/*m/e* 110	
	Found	Calcd[a)]	Found	Calcd[a)]
N*P-0	8.8%	5.9%	8.3%	7.0%
N*P-5	14.1	10.8	16.1	11.9
N*P-30	51.6	48.8	52.4	49.9

a) Calculated on the assumption that the ratios of ^{15}N and ^{14}N in the nitriles are nearly equal to the corresponding N*P.

ed from the cyclohexanone–N*P complexes according to the procedure described above (Eq. 2). The IR and mass spectra of these products were in fair agreement with those of the products which had been derived from the 6-(hydroxyimino)valeric-^{15}N acid (Eq. 4).

These facts indicate that the nitrogen atom in the functional group, *i.e.*, hydroxyimino or cyano group, is definitely introduced from the nitrosyl ligand of NP through the nitrosolysis of cyclohexanone under either the alkaline or the acidic condition.

Discussion on the Nitrosolysis of Cycloalkanones by Use of NP. There were a number of compounds which form colored complexes with NP. Ketones and aldehydes containing active methylene group showed a red, orange or violet color in an alkaline medium. These colors turned to bluish when the solution was made acidic.[6] For example, a deep coloration occurred when aqueous alkaline solution containing acetone or acetophenone was mixed with aqueous NP solution. The color gradually faded untill the final solution was yellow, producing pentacyanoaquoferrate(II) ion and α-hydroxyimino derivatives of the corresponding ketones, as shown in Eq. 6.[7-9] The colored complex should be formed by an electrophilic attack of the nitrosyl ligand to the active methylene. Therefore, NP acted like a nitrosation reagent, such as alkyl nitrites, in the reaction.

$$CH_3CO\text{-}Y \xrightarrow{NP,\ OH^-} \text{colored complex} \longrightarrow [Fe(CN)_5H_2O]^{4-} + HON{=}CHCO\text{-}Y \quad (6)$$
$$(Y = CH_3\text{-},\ C_6H_5\text{-})$$

For example, when an aqueous solution of the colored acetophenone–NP complex was made acidic, very soon a flocculent precipitate of α-(hydroxyimino)-acetophenone separated out, but no nitrosolysis products were formed under this condition. However, cycloalkanone–NP complexes reacted in a similar manner to give ω-cyanoalkanoic acids under the acidic conditions, in general. The ω-cyanoalkanoic acid could result from fission of a carbon–carbon bond of the corresponding 2-(hydroxyimino)cycloalkanone present as a ligand of the colored cycloalkanone–NP complex, a prusso complex, as shown in Fig. 4.

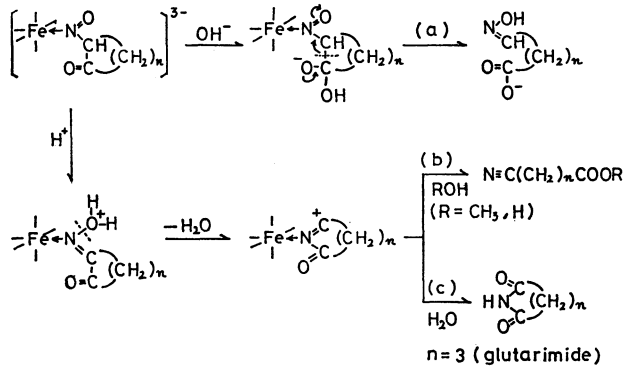

Fig. 4. A possible nitrosolysis reaction route of cycloalkanones using NP.

These facts indicate that the 2-(hydroxyimino)-cycloalkanone present as the ligand of the prusso complex should be in a labile state. The lability would be caused by a ring tension or an electron deficiency of the nitrogen atom under the influence of the electron-withdrawing effect of the central metal ion. In this way the carbon–carbon bond cleavage of the ligand occurred by hydrolysis even under the alkaline condition and gave ω-(hydroxyimino)alkanoic acids in a good yield (see Fig. 4a). Under the acidic condition another solvolytic carbon–carbon bond cleavage of the ligand occurred by Beckmann fission, a Beckmann rearrangement of an abnormal type[10] in the coordination sphere, and gave ω-cyanoalkanoic acids and their esters (see Fig. 4b). The Beckmann rearrangement of the normal type also occurred in a special case by use of cyclopentanone–NP complex. The ligand of this complex, 2-(hydroxyimino)cyclopentanone, was rearranged by acid into the more stable six-membered cyclic imide, *i.e.*, glutarimide (see Fig. 4c).

Experimental

All melting points were uncorrected. The IR spectra were obtained on a Hitatchi EPI S-2 infracord. The NMR spectra were obtained on a Nippon Denshi JNM-PS-100. The mass spectra were obtained on a Hitatchi RMU-6E spectrometer.

Reagent grade sodium pentacyanonitrosylferrate(II) hydrate (NP) and cycloalkanones were used without purification, while cyclohexanone was purified just before use by distillation under reduced pressure. Sodium nitrites-^{15}N (^{15}N contents: 5% and 30%) were obtained from The British Oxygen Co.,

Preparation of Cycloalkanone–NP Complexes. Cycloalkanone (0.05 mol) and sodium hydroxide(0.10 mol) were dissolved in 100 ml methanol. After having been cooled in an ice bath, the solution was poured into a solution of NP (0.05 mol) in 300 ml methanol and then the mixture was stirred for one hour at 0°C. The red-violet or red-brown colored complex was produced during the reaction. After the reaction had been completed, the solvent was removed under vacuum at room temperature to obtain a wet residue: crude cycloalkanone–NP complex.

The Alkaline Hydrolysis of the Cycloalkanone–NP Complex. The alkaline hydrolysis (Eq. 1) was performed by means of the following procedure. After the crude complex had been treated with 10% aqueous sodium hydroxide solution for one hour under reflux, the hydrolysate was filtered. After the filtrate had been extracted with ether to remove the unchanged ketone, the aqueous layer made acidic and was extracted with ether to separate the reaction product: ω-(hydroxyimino)-alkanoic acid was precipitated as colorless needles upon recrystallization from methyl acetate.

The Acid Hydrolysis of the Cycloalkanone–NP Complex. The acid hydrolysis (Eq. 2) was performed by means of the following procedure. After having been made acidic to pH 3 with an appropriate acid, such as phosphoric acid or others, the aqueous solution of the crude complex stood for 24 h at room temperature, and was then extracted with ether. The reaction products and the unchanged ketone were separated from the ethereal extract by fractional distillation under reduced pressure. The products, ω-cyanoalkanoic acid and its methyl ester, were derived into the corresponding crystalline *p*-bromophenacyl ester and were identified.

The by-product, glutarimide, produced from cyclopentanone–NP complex was confirmed by direct comparison with an authentic sample prepared from glutaric anhydride.

Preparation of 2-(Hydroxyimino)cyclododecanone from the Complex. After the crude cyclododecanone–NP complex, which was

prepared by the method described above, had been dissolved in water, the solution(pH 12) was extracted with ether. 2-(Hydroxyimino)cyclododecanone was separated from the ethereal extract; yield 0.2 g (from 0.05 mol cyclododecanone), mp 71—72 °C. Found: C, 68.15; H, 10.39; N, 6.65%. The IR, NMR, and mass spectral data corresponded to the authentic sample prepared by the other method by use of nitrosyl chloride.[3] After having been made acid to pH 3.5 with 6 M hydrochloric acid, the residual aqueous layer was extracted with ether. 11-Cyanoundecanoic acid was separated from the extract; yield 0.4 g, mp 52—54 °C.

Isolation of the Cyclododecanone–NP Complex. Three grams of cyclododecanone was dissolved in a sodium methylate solution prepared from sodium(0.5 g) and anhydrous methanol (35 ml). To the solution 5.0 g of NP in 65 ml of anhydrous methanol was added slowly and stirred for one hour. After the reaction had been completed, the mixture was concentrated to 35 ml under reduced pressure and was poured into 200 ml of anhydrous ethanol to precipitate the complex. The precipitate was separated by means of centrifugation, washed, and dried under reduced pressure. The pure complex was a reddish violet powder; IR: 3400(broad, νOH), 2850 and 2920 (νCH), 2040(sharp, νC≡N, bonded to Fe), 1660(weak, νC=O), 1610 and 1560 cm^{-1}; NMR: δ 1.35, 2.2(q) and 7.24(t) ppm (DMSO-d_6).

Hydrolysis of the Cyclododecanone–NP Complex. The purified cyclododecanone–NP complex(7.2 g, 14 mmol) was dissolved in 100 ml of water, and the solution was extracted with ether. 2-(Hydroxyimino)cyclododecanone was separated from the ethereal extract; yield 1.7 g(8 mmol). After having been made acid to pH 3.0 with 3M sulfuric acid, the residual aqueous layer was extracted with ether. 11-Cyanoundecanoic acid was separated from the extract; yield 1.0 g(4 mmol).

*Preparation of ^{15}N Labeled NP (N*P).* The general method of preparation of the N*P is as follows. Sodium nitrite containing an appropriate amount of ^{15}N was dissolved in an aqueous solution of sodium hexacyanoferrate(II). After an aqueous solution of barium chloride had been added to the solution, carbon dioxide was bubbled into the solution with stirring at 100 °C, and then the solution was filtered to remove barium carbonate. The appropriate amount of ethanol was added to the filtrate to precipitate sodium chloride. The red crystalline N*P was separated from the supernatant liquor by concentration.

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References

1) O. Touster, *Org. React.*, Vol. VII, 327 (1953).
2) A. F. Ferris, G. S. Johnson, and F. E. Gould, *J. Org. Chem.*, **25**, 496 (1960).
3) M. Kataoka and M. Ohno, *Bull. Chem. Soc. Jpn.*, **46**, 3474 (1973).
4) M. M. Rogić, J. Vitrone, and M. D. Swerdloff, *J. Am. Chem. Soc.*, **97**, 3848 (1975).
5) T. Shono, H. Nii, and K. Shinra, *Kogyo Kagaku Zasshi*, **72**, 1669 (1969).
6) F. Feigle, "Qualitative Analyse Tüpfelreaktionen," (1938), p. 396.
7) K. W. Lauch and T. A. Turney, *J. Inorg. Nucl. Chem.*, **18**, 179 (1961).
8) J. H. Sweinhart and W. G. Schmidt, *Inorg. Chem.*, **6**, 232 (1967).
9) S. K. Wolfe and J. H. Sweinhart, *Inorg. Chem.*, **7**, 1855 (1968).
10) A. F. Ferris, *J. Org. Chem.*, **25**, 12 (1960).