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THE PILOTY-ROBINSON REACTION OF N-SUBSTITUTED PIPERIDIN-4-ONE AZINES. A NOVEL ROUTE FOR THE SYNTHESIS OF 3,6-DIAZACARBAZOLE

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The possibility of preparing 1,2,3,4,6,7,8,9-octahydro-5H-pyrrolo[3,2-c:4,5-c']dipyridines using the Piloty-Robinson reaction has been studied under various conditions. A novel method is proposed for the synthesis of the aromatic 3,6-diazacarbazole (5H-pyrrolo[3,2-c:4,5-c']dipyridine) from 2,8-dibenzoyl-1,2,3,4,6,7,8,9-octahydro-5H-pyrrolo[3,2-c:4,5-c']dipyridine obtained for the first time by the Piloty-Robinson method under thermal conditions.

Keywords: 8-aza-γ-carboline, 2',3a',4',5',6',7'-hexahydrospiro[piperidine-4,3'-pyrazolo[4,3-*c*]pyridines], 3,6-diazacarbazole, 5H-pyrrolo[3,2-*c*:4,5-*c*"]dipyridine, Piloty-Robinson synthesis of pyrroles, [3,3] sigmatropic rearrangement.

In 1960 O. Piloty discovered that diethyl ketone azine with an excess of anhydrous zinc chloride was converted to 2,5-diethyl-3,4-dimethylpyrrole at 230ºC in 25% yield [1]. G. and R. Robinson reported in 1918 that heating desoxybenzoin azine at 180ºC in a stream of hydrogen chloride gave 2,3,4,5-tetraphenylpyrrole in 88% yield [2]. This method of preparing pyrroles by heating the corresponding carbonyl compound azines in the presence of an acidic reagent has since been called the Piloty-Robinson reaction [3]. In a series of studies [1, 2, 4, 5] there were undertaken unsuccessful attempts to extend this synthetic route to azines of other carbonyl compounds, *viz*: butyric and isovaleric aldehydes, acetone, cyclopentanone, butyrone, and acetophenone. However, cyclohexanone azine (**1**) could be successfully cyclized to 2,3,4,5,6,7,8,9-octahydro-1H-carbazole (**2**) by refluxing in tetralin in an HCl atmosphere in 28% yield [6]. A. N. Kost and I. I. Grandberg reported [5] that compound **2** could be prepared in 79% yield by heating the azine **1** with anhydrous zinc chloride and also that the N-acetyloctahydrocarbazole could be prepared in 82% yield by refluxing in dioxane with acetyl chloride.

It was thought that the mechanism of the Piloty-Robinson reaction is similar to that of the Fischer synthesis of indoles. Acid causes a tautomeric conversion of the azine to the bisenehydrazine which undergoes a [3,3] sigmatropic rearrangement accompanied by formation of a novel C–C bond and cleavage of the N–N bond with closure to a pyrrole ring *via* loss of a molecule of ammonia [2, 7].

Dedicated to Academician V. N. Charushin on his 60th birthday.

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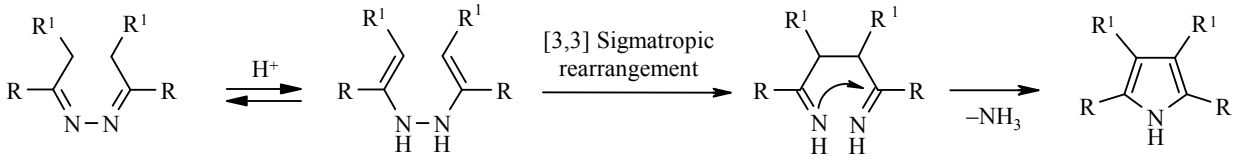
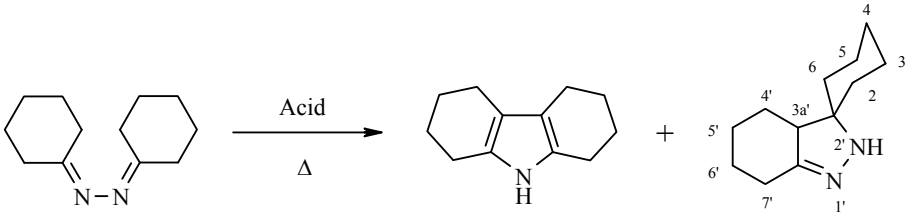


R, R1 = Ar, Alk, H

The Piloty-Robinson method remained quiescent for a long time but modifications have appeared in recent years. Thus methods for preparing pyrroles containing both symmetrically [8] and unsymmetrically placed substituents have been proposed [9, 10]. In addition, variants of the Piloty-Robinson synthesis have been reported using microwave irradiation [11], solid-phase synthesis [12] or base catalysis [13] conditions.

In the first stage of this work we decided to develop a preparative method for obtaining the octahydrocarbazole **2** from azine **1** using acid catalysts such as *p*-toluenesulfonic acid and PPA (Table 1).

From the data obtained it is clear that use of 2 equivalents of *p*-toluenesulfonic acid gives the target octahydrocarbazole **2** in maximum yield. It should be noted that the Piloty-Robinson reaction can be accompanied by the formation of a side compound (the spiropyrazole **3**), the structure of which was proposed in studies [14, 15] but established by the authors only from elemental analytical data and from a chain of chemical reactions which finally led to 1-cyclohexylcyclohexene. In fact, from our data, the spiropyrazoline **3** is indeed formed in a significant amount in the case of *p*-toluidine hydrochloride. Characteristic for the ^{1}H NMR spectrum of compound **3** (compared with that of compound **2**) is the appearance of a multiplet signal for the H-3*a* proton at 2.61 and a broadened NH proton signal at 4.79 ppm while the signal for the proton of the NH group in compound **2** is found at 7.35 ppm.



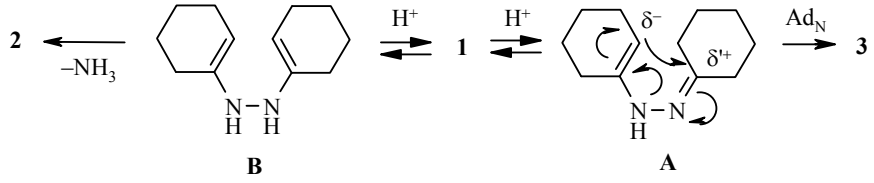
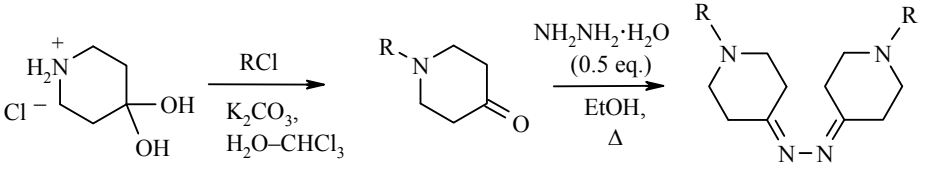


TABLE 1. Conditions for Cyclization of Azine **1** and Yields of Compounds **2** and **3**

Method	Conditions	Yield, %	
		2	**3**
A	PPA, 180°C, 5 min	85	–
B	TsOH (2 eq.), toluene, refluxing, 4 h, Ar atmosphere	95	–
C	TsOH (1.5 eq.), toluene, refluxing, 4 h, Ar atmosphere	85	5
D	*p*-Toluidine hydrochloride (1.5 eq.), dioxane, refluxing, 4 h	60	35

According to the data in Table 1 a decrease in the acidity of the medium leads to an increase in the content of the spiro compound **3** in the reaction mixture. This may be due to the fact that, under conditions of insufficient acidity, takes place the shift in the equilibrium concentration to the enamino-imine form **A** which cyclizes to the spiropyrazoline **3** while the biseneamine form **B** serves as the intermediate for formation of carbazole **2**.

Up to this time there has been no evidence for the potential use of azines of heterocyclic ketones in the Piloty-Robinson reaction. Hence we have studied the reaction of the azines of 1-substituted piperidin-4-ones **4** in the presence of an acid catalyst with a view to preparing the corresponding 1,2,3,4,6,7,8,9-octahydro-5H-pyrrolo[3,2-*c:*4,5-*c*']dipyridines **5**. At this time only one synthetic method has been reported [16] and this is based on the annelation of two tetrahydropyridine rings onto a pyrrole ring. Our method, based on the Piloty-Robinson reaction, involves the construction of the tricyclic diazacarbazole system **5** *via* formation of the pyrrole ring. The starting azines **4** (Table 2) were prepared from the corresponding piperidin-4-ones **6** by the following sequence of reactions:



6a–d **4a–f**

4,6 a R = Ac, **b** R = Bz, **c** R = Ms, **d** R = Ts; **4 e** R = Me, **f** R = Bn

We have carried out the cyclization of the azines **4** under the conditions developed in the case of the cyclohexylideneazine (**1**). For the azines **4a–d** two equivalents of TsOH were used while, for the azines **4e,f**, it was necessary to use four equivalents of TsOH so that both tertiary nitrogen atoms occurred in the protonated form. We also carried out the reaction with 1.5 equivalents of *p*-toluidine hydrochloride in order to study the effect of the nature of the catalyst on the course of the cyclization of azines **4a–d** (Table 3).

TABLE 2. Characteristics of the Synthesized Piperidin-4-ones **4**

Compound	Empirical formula	Found, % / Calculated, %			mp., °C	Yield, %
		C	H	N		
4a	$C_{14}H_{22}N_4O_2$	60.36 / 60.41	7.92 / 7.97	20.00 / 20.13	172–173	78
4b	$C_{24}H_{26}N_4O_2$	71.63 / 71.62	6.58 / 6.51	13.91 / 13.92	210–211	93
4c*	$C_{12}H_{22}N_4O_4S_2$	41.44 / 41.13	6.46 / 6.33	16.01 / 15.99	281–282 (decomp.)	77
4d*²	$C_{24}H_{30}N_4O_4S_2$	57.52 / 57.35	6.14 / 6.02	11.06 / 11.15	289–290 (decomp.)	79
4e	$C_{12}H_{22}N_4$	64.64 / 64.83	10.05 / 9.97	25.31 / 25.20	65–66	59
4f	$C_{24}H_{30}N_4$	77.14 / 76.97	7.97 / 8.06	14.85 / 14.96	109–110	90

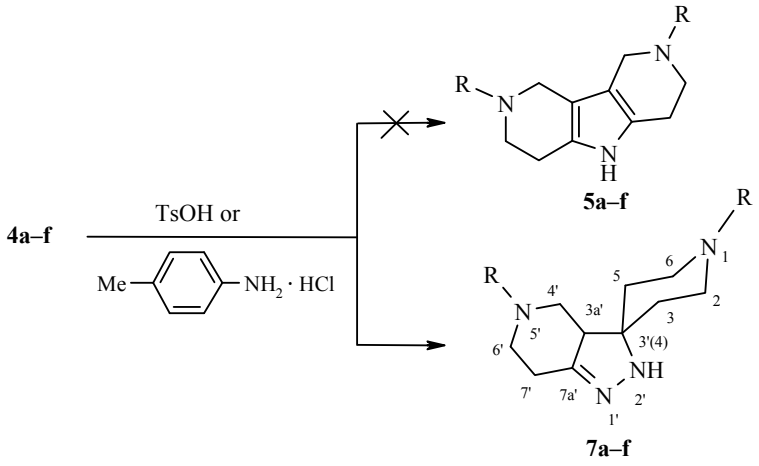
* Found, %: S 17.99; calculated, %: S 18.30.

*² Found, %: S 12.70; calculated, %: S 12.76.

TABLE 3. Cyclization Conditions for Azines **4a–f** and Yields of Pyrazolo[4,3-*c*]pyridines **7**

Ketazine	Method	Compound **7**	Yield, %
4a	A (*p*-toluidine hydrochloride)	**7a**	66
	B (2 eq. TsOH)	**7a**	43
4b	A (*p*-toluidine hydrochloride)	**7b**	62
	B (2 eq. TsOH)	tarring	
4c	A (*p*-toluidine hydrochloride)	**7c**	0*
	B (2 eq. TsOH)	**7c**	0*[2]
4d	A (*p*-toluidine hydrochloride)	**7d**	0*
	B (2 eq. TsOH)	**7d**	0*[2]
4e	C (4 eq. TsOH)	**7e**	79
4f	C (4 eq. TsOH)	**7f**	77

* Starting azine isolated in quantitative yield.
*[2] Isolated products could not be identified.



a R = Ac, **b** R = Bz, **c** R = Ms, **d** R = Ts, **e** R = Me, **f** R = Bn

It should be noted that, in contrast to the cyclohexylideneazine, the cyclization of the azines **4a,b,e,f** in acid conditions gives the corresponding pyrazolopyridines **7** (Tables 3 and 4), the octahydrodiazacarbazoles **5** not being observed amongst the reaction products. For the azines **4c,d** the use of two equivalents of the TsOH gave compounds which structures could not be determined.

The ^{1}H NMR spectra of compounds **7a** and **7b** appeared as mixtures of amidine rotamers, characterized by the existence of several sets of signals in different ratios due to the presence of the acetyl and benzyl substituents respectively. The ^{13}C NMR spectra were uninformative for the same reason. The derivative **7f** gave a ^{1}H NMR spectrum with a rather complex pattern of multiplet signals for the aliphatic protons. In order to achieve an exact assignment of the proton and carbon atom signals for the aliphatic region, we carried out additional homo- (COSY ^{1}H–^{1}H NMR) and heteronuclear (^{1}H–^{13}C) 2D NMR experiments (Table 5) on the basis of which we have made the signal assignments for the analogous compound **7e**. The structure of the spiro compounds **7** was confirmed by X-ray analytical data for the N-methyl substituted derivative **7e** (Figure 1, Tables 6 and 7).

TABLE 4. Characteristics of the 2',3a',4',5',6',7'-Hexahydrospiro-[piperidine-4,3'-pyrazolo[4,3-*c*]pyridines] **7**

Compound	Empirical formula	Found, % / Calculated, %			mp., °C	*m/z* $[M]^+$
		C	H	N		
7a	$C_{14}H_{22}N_4O_2$	60.61 / 60.41	7.85 / 7.97	20.15 / 20.13	193–194	278
7b	$C_{24}H_{26}N_4O_2$	71.46 / 71.62	6.53 / 6.51	13.69 / 13.92	162–163	402
7e	$C_{12}H_{22}N_4 \cdot 3HCl$	43.51 / 43.45	7.66 / 7.60	16.95 / 16.89	225–227 (decomp.)	222
7f	$C_{24}H_{30}N_4$	77.25 / 76.97	8.10 / 8.07	14.81 / 14.96	124–125	374

TABLE 5. Results of the COSY ^1H–^1H and ^1H–^{13}C Experiments for Compound **7f**

Atom groups	^1H NMR Spectrum, δ, ppm	Chemical shifts of the correlated protons, δ, ppm	Cross peaks in the ^{13}C measurement, δ, ppm
H-5	1.57–1.62	2.11–2.23, 2.67–2.76	31.46
H-7'	1.65–1.71	1.81, 2.11–2.23, 2.67–2.76	37.58
H-7'	1.81	1.65–1.71, 2.11–2.23, 2.67–2.76	37.58
H-2 and H-4'	2.02–2.09	2.41–2.50, 2.51–2.56, 2.67–2.76, 2.97, 3.04–3.09	50.92 and 53.51
H-6 and H-6'	2.11–2.23	1.57–1.62, 1.65–1.71, 1.81, 2.67–2.76	53.38 and 53.51
H-3	2.41–2.50	2.02–2.09, 2.51–2.56, 3.04–3.09	27.94
H-3	2.51–2.56	2.02–2.09, 2.41–2.50, 3.04–3.09	27.94
H-6, H-4' and H-6'	2.67–2.76	1.57–1.62, 1.65–1.71, 1.81, 2.02–2.09, 2.11–2.23, 2.97	50.92, 53.38 and 53.51
H-3a'	2.97	2.02–2.09, 2.67–2.76	53.85
H-2	3.04–3.09	2.02–2.09, 2.41–2.50, 2.51–2.56	53.51
$PhCH_2N(1)$	3.50	–	63.23
$PhCH_2N(5')$	3.59	3.62	62.64
$PhCH_2N(5')$	3.62	3.59	62.64

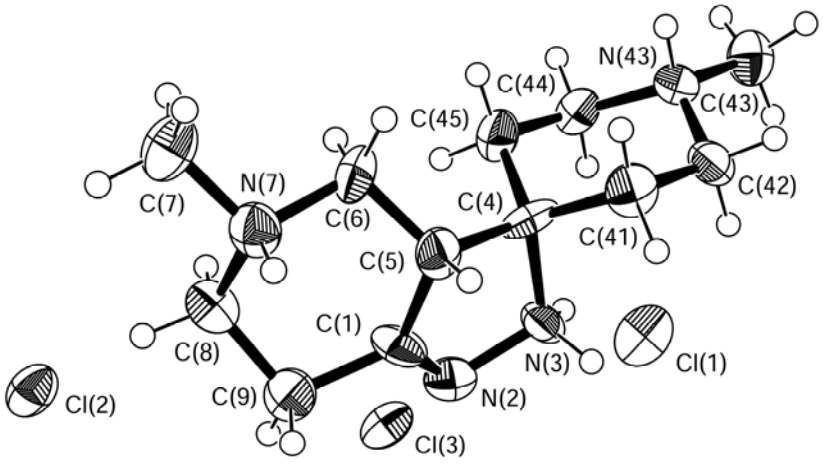


Figure 1. Molecular structure of the compound **7e.**

TABLE 6. Individual Bond Lengths (l) in the Structure **7e**

Bond	*l*, Å	Bond	*l*, Å
C(1)–N(2)	1.257(10)	C(42)–N(43)	1.501(9)
C(1)–C(5)	1.492(11)	N(43)–C(43)	1.476(9)
C(1)–C(9)	1.556(12)	N(43)–C(44)	1.525(9)
N(2)–N(3)	1.434(9)	C(44)–C(45)	1.478(10)
N(3)–C(4)	1.565(10)	C(5)–C(6)	1.464(11)
C(4)–C(41)	1.515(10)	C(6)–N(7)	1.534(10)
C(4)–C(5)	1.547(12)	N(7)–C(7)	1.462(10)
C(4)–C(45)	1.531(11)	N(7)–C(8)	1.603(10)
C(41)–C(42)	1.473(10)	C(8)–C(9)	1.500(11)

It follows from the mechanism of the Piloty-Robinson reaction given above that a necessary condition for the occurrence of the key [3,3] sigmatropic rearrangement stage is the presence of a reasonable equilibrium concentration of the bisenehydrazine form. Evidently it is the inadequate concentration of such a form in acid catalysis conditions that serves as the reason for the absence of the dicarbazole **5** among the reaction products. With the bis acylated azines the needed formation of the bisenehydrazine form is achieved [9] and this cyclizes to the corresponding N-acylpyrrole when refluxed in xylene. Based on this data we have studied the potential cyclization of the dibenzoyl azine derivative **4f** under thermal conditions.

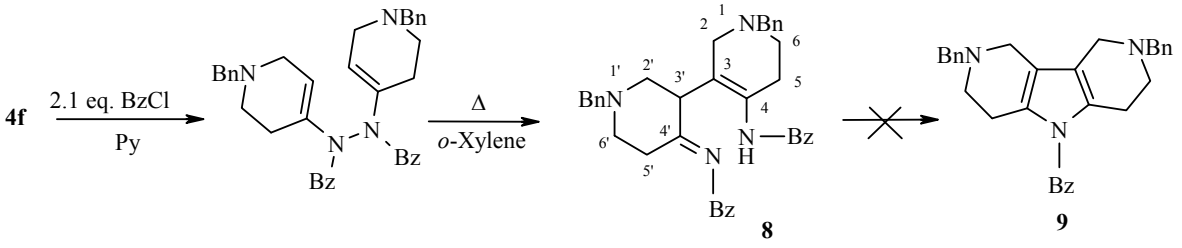
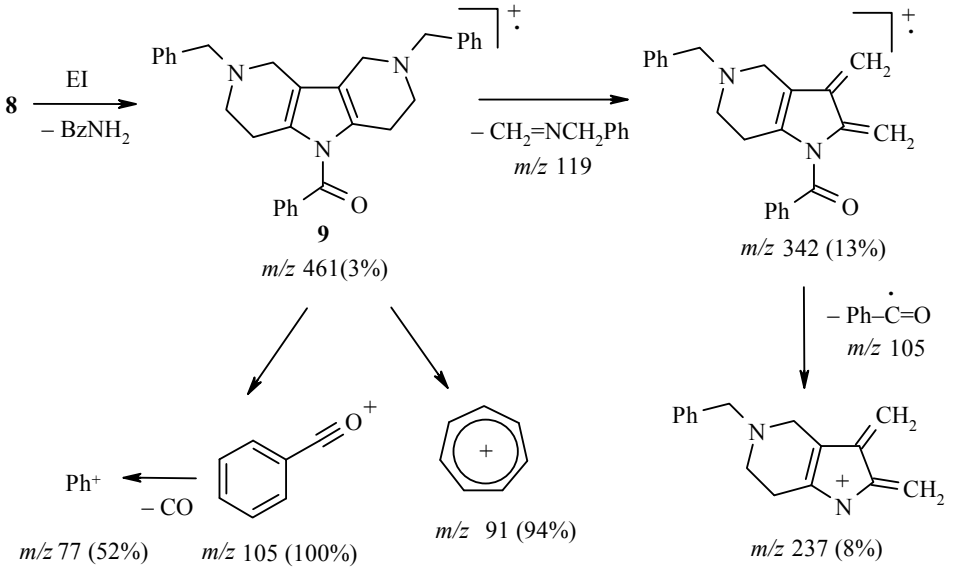


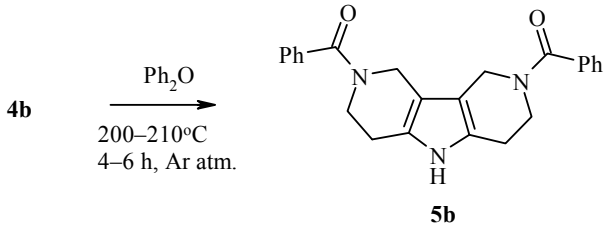
TABLE 7. Individual Valence Angles (ω) in the Structure **7e**

Angle	ω, deg	Angle	ω, deg
N(2)–C(1)–C(5)	120.2(9)	C(43)–N(43)–C(44)	112.9(6)
N(2)–C(1)–C(9)	119.9(9)	C(42)–N(43)–C(44)	111.7(7)
C(5)–C(1)–C(9)	119.8(9)	C(45)–C(44)–N(43)	112.8(7)
C(1)–N(2)–N(3)	102.5(8)	C(44)–C(45)–C(4)	112.2(8)
N(2)–N(3)–C(4)	111.3(7)	C(6)–C(5)–C(1)	114.5(8)
C(41)–C(4)–C(5)	114.7(8)	C(6)–C(5)–C(4)	118.6(8)
C(41)–C(4)–C(45)	111.3(8)	C(1)–C(5)–C(4)	101.4(8)
C(5)–C(4)–C(45)	112.7(8)	C(5)–C(6)–N(7)	110.4(8)
C(41)–C(4)–N(3)	108.8(8)	C(7)–N(7)–C(6)	110.9(7)
C(5)–C(4)–N(3)	96.8(8)	C(7)–N(7)–C(8)	109.2(7)
C(45)–C(4)–N(3)	111.8(7)	C(6)–N(7)–C(8)	106.3(6)
C(42)–C(41)–C(4)	112.5(7)	C(9)–C(8)–N(7)	108.8(7)
C(41)–C(42)–N(43)	113.5(7)	C(8)–C(9)–C(1)	108.7(8)
C(43)–N(43)–C(42)	114.7(7)		

It was found, however, that treatment of azine **4f** with 2.1 equivalents of benzoyl chloride in the presence of pyridine as a base and subsequent refluxing in xylene for 36 h did not give the expected carbazole **9**, the single reaction product **8** (in 92% yield) being the result of a sigmatropic rearrangement. In our view this result is of considerable interest from the viewpoint of confirming the route of the Piloty-Robinson reaction as a [3,3] sigmatropic rearrangement occurring with the formation of a C–C bond and cleavage of the N–N bond. Attempts to cyclize compound **8** by heating in diphenyl oxide at 180–200ºC did not yield the carbazole **9** but led to its thermal degradation. However, on study of the mass spectrum of compound **8**, it was found that it does not show a molecular ion but undergoes cyclization under EI conditions to compound **9** as indicated by subsequent fragment [the *m/z* (I_{rel}, %) values for the fragments are reported]:



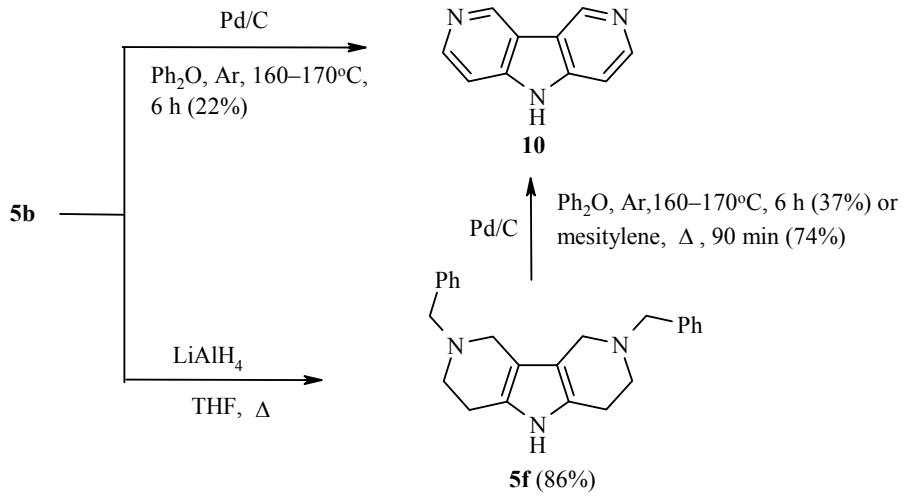
Since the Piloty-Robinson reaction takes place *via* a [3,3] sigmatropic rearrangement mechanism, we considered that it might occur at high temperature without a catalyst and this has not been reported previously in the literature. In fact, a positive result (i.e. the preparation of the target octahydro-3,6-diazacarbazole **5**) was achieved under thermal conditions and in 95% yield without an acid catalyst by using the dibenzoylazine **4b** at 210–220ºC in diphenyl oxide over 4–6 h.



5b

The cyclization does not occur at lower temperatures (160–170ºC) and the starting azine **4b** is isolated in 96% yield. The cyclization of azines **4a,c–f** under thermal conditions could not be achieved. Hence at 160–170ºC all of the azines returned the starting materials: **4a** (80%), **4c,d** (quantitative), **4e** (84%), **4f** (65%). Increasing the temperature to 210–220ºC for the azines **4a,e,f** led to tarring of the reaction mixtures and the azines **4c,d** were separated unchanged.

Because the ultimate aim of our work is the preparation of the aromatic 3,6-diazacarbazole (**10**) we have studied the possible aromatization of the octahydro derivative **5b** by various routes. The first consists of simultaneous debenzoylation and oxidation using Pd/C in diphenyl oxide at 160–170ºC in an argon atmosphere (method A). In the second, initial reduction by $LiAlH_4$ was assumed to give the dibenzyl derivative **5f** with its subsequental debenzylation and aromatization in the presence of Pd/C by heating in diphenyl oxide in an inert atmosphere (method B) or by refluxing in mesitylene (method C).



The yield of compound **10** by method C proved to be optimal hence we are able to propose a novel route for preparation of the 3,6-diazacarbazole **10** in five stages in overall 55% yield based on the starting piperidin-4-one hydrochloride monohydrate.

EXPERIMENTAL

^1H and ^{13}C NMR spectra were recorded on a Bruker-400 (400 and 100 MHz respectively) with the use of double resonance (^1H–^1H), APT, and 2D COSY (^1H–^1H and ^1H–^{13}C) spectroscopic methods. The chemical shifts were measured relative to the signals of the remaining solvent protons in the DMSO-d_6 and $CDCl_3$ (2.51 and 7.27 ppm respectively). Mass spectra were taken on a Finnigan MAT ITD-700 instrument using EI, 70 eV ionization energy, and mass spectral range *m/z* 45 to 400. Monitoring of the reaction course and the purity of the compounds prepared was carried out by TLC on Silufol UV-254 plates in the system ethyl acetate–methanol (2:1).

X-ray Structural Analysis of Compound 7e. Crystals of **7e** were grown in methanol at 22ºC and are monoclinic with a = 11.258(3), b = 6.8667(12), c = 25.039(5) Å, β = 98.56(2)º, V = 1914.1(7) Å^3, M_r = 331.71, Z = 4, space group $P2_1/n$, d_{calc} = 1.151 g/cm^3, μ(AgKα) = 0.245 mm^{-1}, F(000) = 704. The unit cell parameters and intensities of 2766 reflections (2439 independent, R_{int} = 0.0341) were measured on a CAD4 diffractometer [17] (AgKα radiation, point scintillation detector, graphite monochromator, ω-scanning, θ_{max} = 18º).

The structure was solved by the direct method using the SHELXS97 program package [18]. The positions of all of the hydrogen atoms were revealed in electron density difference synthesis and the refinement was carried out using the "riding" model. The structure was refined by F^2 full matrix least squares analysis in the anisotropic approximation for non-hydrogen atoms to wR_2 = 0.0607 for 4205 reflections (R_1 = 0.0421 for 2439 reflections with $F^2 > 2\sigma(F^2)$) with S = 0.562 using the SHELXL97 program package [18]. The numbering of the atoms in the compound studied and its geometric structure are illustrated in Figure 1 using the ORTEP-3 program [19]. The full crystallographic information has been placed in the Cambridge Structural Database as deposit CCDC 812271.

Cyclohexylideneazine (1) was prepared by method [6]. Yield 72%; mp 32–33ºC (mp 33ºC [6]). ^{1}H NMR spectrum, δ, ppm: 1.58–1.65 (8H, m, H*a*-3(5) and H-4); 1.70–1.76 (4H, m, H*e*-3(5)); 2.31–2.34 (4H, m, H*a*-2(6)); 2.37–2.40 (4H, m, H*e*-2(6)).

2,3,4,5,6,7,8,9-Octahydro-1H-carbazole (2). A. A mixture of azine **1** (8.0 g, 41.7 mmol) and PPA (40 g) [20] was heated to 150–160ºC with stirring and the reaction mixture self heated to about 200ºC. The product was held at 180ºC for a further 5 min, cooled, dissolved in cold water, and extracted with chloroform (4×50 ml). The extract was washed with saturated sodium bicarbonate solution, dried over sodium sulfate, evaporated to dryness, and a further twice evaporated with toluene (10 ml) to constant weight to give the product as a yellow oil (6.2 g, 85%) which crystallized in the cold; mp 95ºC (mp 96ºC [5]). The compound obtained was unstable to storage in air. ^{1}H NMR spectrum, δ, ppm: 1.77–1.89 (8H, m, H-2,3,6 and 7); 2.43–2.46 (4H, m, H-4 and H-5); 2.58–2.61 (4H, m, H-1 and H-8); 7.35 (1H, br s, NH).

B. A solution of *p*-toluenesulfonic acid monohydrate (15.9 g, 83.7 mmol) was dehydrated by azeotropic distillation using toluene. Azine **1** (8.0 g, 41.7 mmol) was added to the solution obtained (of volume ~ 50 ml) and the reaction mixture was refluxed for 4 h under an argon atmosphere, cooled, diluted with water, and basified using ammonia solution (25%). The organic phase was separated and the aqueous phase was extracted with chloroform (3×50 ml). The combined extracts were dried over sodium sulfate and evaporated to dryness to give light-yellow oil which crystallized in the cold; mp 96ºC (petroleum ether). The ^{1}H NMR spectrum was identical to that obtained using method A.

C. Similarly to method B but using *p*-toluenesulfonic acid monohydrate (11.9 g, 62.6 mmol) to give brown oil (6.8 g), which was chromatographed on silica gel. Octahydrocarbazole **2** (6.2 g, 85%) was obtained as a yellow oil (eluent benzene) which crystallizes in the cold (mp 94–95ºC) and also the **2',3a',4',5',6',7'-hexahydrospiro[cyclohexane-1,3'-indazole] (3)** (eluent chloroform) as a gray, crystalline material with mp 62–63ºC (mp 63ºC [5]). ^{1}H NMR spectrum, δ, ppm: 1.27–1.57 (13H, m, H-2,3,4,5,6 and H-5',6'); 1.76–1.94 (3H, m, H-4' and H-6'); 2.08–2.16 (1H, m, H*a*-7'); 2.33–2.38 (1H, m, H*e*-7'); 2.59–2.63 (1H, m, H-3*a*'); 4.97 (1H, br. s, NH).

D. A suspension of azine **1** (8.0 g, 41.7 mmol) and *p*-toluidine hydrochloride (9.0 g, 62.6 mmol) in dioxane (50 ml) was refluxed for 4 h. The product was cooled, the dioxane was evaporated, water (50 ml) was added followed by ammonia solution (25%), and then extracted with chloroform (4×50 ml). The extract was dried over sodium sulfate, evaporated to dryness, and chromatographed on silica gel as in method C to give the octahydrocarbazole **2** (4.4 g, 60%) and the indazole **3** (2.8 g, 35%). The physicochemical characteristics of compounds **2** and **3** were identical to those given above.

N-Acyl- and **N-Sulfonylpiperidin-4-ones (6a–d) (General Method)**. Potassium carbonate (33.0 g, 240 mmol) was added portionwise to a solution of piperidin-4-one hydrochloride monohydrate (15.4 g, 100 mmol) in water (100 ml) followed by dichloromethane (100 ml). A solution of the acyl- or sulfonyl chloride (105 mmol) in dichloromethane (60 ml) was then added dropwise with stirring. The reaction mixture was stirred for 3 h at 25ºC. The organic phase was separated, washed with a solution of sodium bicarbonate, dried over sodium sulfate, and evaporated to dryness. As judged from ^{1}H NMR data the N-substituted piperidin-4-ones **6a–d** obtained in this way were satisfactory for further use without additional purification.

N-Acetylpiperidin-4-one (6a). Colorless oil. Yield 94%. ^{1}H NMR spectrum, δ, ppm: 2.13 (3H, s, CH_3); 2.39–2.46 (4H, m, H-3(5)); 3.70–3.73 (2H, m, H-2); 3.80–3.83 (2H, m, H-6).

N-Benzoylpiperidin-4-one (6b). Light-yellow, viscous oil, crystallizing over 4–5 weeks in the cold. Yield 97%; mp 50–51ºC (49–52ºC [21]). ^{1}H NMR spectrum, δ, ppm: 2.32–2.59 (4H, m, H-3(5)); 3.62–4.03 (4H, m, H-2(6)); 7.38–7.45 (5H, m, Ph).

N-(Methylsulfonyl)piperidin-4-one (6c). White crystalline material. Yield 52%; mp 102–103ºC (102–104ºC [22]). ^{1}H NMR spectrum, δ, ppm: 2.57–2.61 (4H, m, H-3(5)); 2.90 (3H, s, CH_3); 3.58–3.61 (4H, m, H-2(6)).

N-[(4-Methylphenyl)sulfonyl]piperidin-4-one (6d). White crystalline material. Yield 98%; mp 129–130ºC (129–131ºC [23]). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.45 (3H, s, CH_3); 2.53–2.56 (4H, m, H-3(5)); 3.38–3.41 (4H, m, H-2(6)); 7.36 (2H, d, *J* = 8.2, H-3(5) Ar); 7.69 (2H, d, *J* = 8.2, H-2(6) Ar).

Ketazines 4a–f (General Method). Hydrazine hydrate (1.5 g, 30 mmol) was added dropwise with vigorous stirring to a solution of the corresponding piperidin-4-one (60 mmol), refluxed for 5 min, and left to cool in the fridge. The precipitated crystals were filtered off and dried in air.

N-Acetylpiperidin-4-ylideneazine (4a). White crystalline material. ^{1}H NMR spectrum, δ, ppm: 2.16 (6H, s, 2CH_3); 2.49–2.55 (4H, m, H*a*-3(5)); 2.59–2.71 (4H, m, H*e*-3(5)); 3.55–3.79 (8H, m, H-2(6)).

N-Benzoylpiperidin-4-ylideneazine (4b). White crystalline material. ^{1}H NMR spectrum, δ, ppm: 2.38–2.83 (8H, m, H-3(5)); 3.48–4.01 (8H, m, H-2(6)); 7.38–7.49 (10H, m, 2Ph).

N-(Methylsulfonyl)piperidin-4-ylideneazine (4c). White crystalline material. ^{1}H NMR spectrum (DMSO-d_6), δ, ppm: 2.48–2.51 (4H, m, H*a*-3(5)); 2.61–2.64 (4H, m, H*e*-3(5)); 2.92 (6H, s, 2CH_3); 3.23–3.26 (4H, m, H-2(6)); 3.34–3.37 (4H, m, H-2(6)).

N-[(4-Methylphenyl)sulfonyl]piperidin-4-ylideneazine (4d). White crystalline material. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.44 (6H, s, 2CH_3); 2.50–2.53 (4H, m, H*a*-3(5)); 2.66–2.69 (4H, m, H*e*-3(5)); 3.11–3.14 (4H, m, H-2(6)); 3.21–3.24 (4H, m, H-2(6)); 7.32 (4H, d, J = 8.2, H-3(5) Ar); 7.65 (4H, d, J = 8.2, H-2(6) Ar).

N-Methylpiperidin-4-ylideneazine (4e). Cream-colored crystalline material. ^{1}H NMR spectrum, δ, ppm: 2.33 (6H, s, 2CH_3); 2.46–2.50 (8H, m, H-3(5)); 2.56–2.62 (8H, m, H-2(6)).

N-Benzylpiperidin-4-ylideneazine (4f). White crystalline material. ^{1}H NMR spectrum, δ, ppm: 2.47–2.50 (4H, m, H*a*-3(5)); 2.53–2.65 (12H, m, H*e*-3(5) and H-2(6)); 3.57 (4H, s, 2C$\underline{H}_2$Ph); 7.26–7.37 (10H, m, 2Ph).

2',3a',4',5',6',7'-Hexahydrospiro(piperidine-4,3'-pyrazolo[4,3-*c*]pyridines 7a–f (General Method). A. *p*-Toluidine hydrochloride (1.5 mmol) was added to a suspension of the azine **4** (1 mmol) in anhydrous dioxane (10 ml) and refluxed for 4 h, the solvent evaporated, and water (20 ml) was added. The product was basified using ammonia solution (25%) and, for azines **4a,b**, extracted with chloroform (3×30 ml), dried over sodium sulfate, and evaporated to dryness. In the case of the azines **4c,d** the precipitate was filtered, washed with water, and dried in air. In both cases the unpurified compound was washed with ether to remove *p*-toluidine, the solution decanted, and the residue was recrystallized from methanol.

B. A solution of *p*-toluenesulfonic acid monohydrate (0.38 g, 2.0 mmol) was dehydrated by azeotropic distillation of toluene. The azine **4a–d** (1.0 mmol) was added to the solution obtained (volume ~ 30 ml) and the reaction mixture was refluxed for 4 h in an argon atmosphere, evaporated to dryness, diluted with water, basified by ammonia solution (25%), and extracted with chloroform (4×20 ml). The extracts were combined, dried over sodium sulfate, and evaporated to dryness. The residue was recrystallized from methanol.

C. The method was similar to B but, in the case of azines **4e,f**, toluenesulfonic acid monohydrate (0.76 g, 4.0 mmol) was used.

1,5'-Diacetyl-2',3a',4',5',6',7'-hexahydrospiro[piperidine-4,3'-pyrazolo[4,3-*c*]pyridine] (7a). Light-yellow, crystalline material. ^{1}H NMR spectrum (mixture of two rotamers in the ratio 3:7), δ, ppm: 1.55–1.88 (4H, m, H-3,5); 2.12 and 2.13 (3H, 2s, 1-CONCH_3); 2.15 and 2.18 (3H, 2s, 5'-CONCH_3); 2.32–2.44 (1H, m, H-7'); 2.49–2.56 (1H, m, H-7'); 2.60–2.72 (2H, m, H-2(6)); 2.91–3.22 (2H, m, H-2(6)); 3.29–3.40 (1H, m, H-3a'); 3.57–3.78 (1H, m, H-6'); 3.86–3.93 and 4.28–4.42 (1H, 2m, H-6'); 4.01–4.08 and 4.10–4.16 (1H, 2m, H-4'); 4.79–4.84 and 4.88–4.93 (1H, 2m, H-4'); 5.52 (1H, br. s, NH). Mass spectrum, *m/z* (I_{rel}, %): 278 $[M]^+$ (3.1), 235 $[M–Ac]^+$ (6.4), 191 (20.4), 164 (5.5), 137 (14.9), 120 (31.4), 97 (11.7), 82 (11.2), 80 (26.1), 58 (15.4), 56 (16.1), 44 (16.4), 43 (100), 42 (51.8).

1,5'-Dibenzoyl-2',3a',4',5',6',7'-hexahydrospiro[piperidine-4,3'-pyrazolo[4,3-*c*]pyridine] (7b). Cream, crystalline material. ^{1}H NMR spectrum (mixture of several rotamers), δ, ppm: 1.55–2.58 (6H, m, H-3,5,7')); 2.60–3.75 (6H, m, H-2,6,3a',6'); 3.80–5.09 (3H, 2m, H-4',6'); 5.52 (1H, br. s, NH); 7.36–7.52 (10H, m, 2Ph). Mass spectrum, *m/z* (I_{rel}, %): 402 $[M]^+$ (8.1), 401 $[M–H]^+$ (11.6), 297 $[M–Bz]^+$ (6.2), 283 $[M–NBz]^+$ (26.3), 255 (6.2), 241 (8.9), 148 (6.3), 134 (12.4), 120 (15.9), 106 (12.8), 105 $[Bz]^+$ (100), 78 (5.8), 77 $[Ph]^+$ (75.5), 51 (11.2), 42 (7.6).

1,5'-Dimethyl-2',3a',4',5',6',7'-hexahydrospiro[piperidine-4,3'-pyrazolo[4,3-*c*]pyridine] (7e). White crystalline material. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.59–1.62 (2H, m, H-5); 1.64–1.69 (1H, m, H-7'); 1.81 (1H, ddd, J_1 = 13.2, J_2 = 11.0, J_3 = 4.1, H-7'); 1.95–2.02 (2H, m, H-2 and H-4'); 2.09–2.20 (2H, m, H-6 and

H-6'); 2.26 (3H, s, 5'-NCH_3); 2.33 (3H, s, 1-NCH_3); 2.38–2.54 (2H, m, H-3); 2.55–2.67 (2H, m, H-6 and H-6'); 2.72 (1H, dd, J_1 = 11.5, J_2 = 6.1, H-4'); 2.87 (1H, ddd, J_1 = 10.4, J_2 = 6.1, J_3 = 1.7, H-3a'); 2.93–3.00 (1H, m, H-2); 5.23 (1H, br. s, NH). ^{13}C NMR spectrum, δ, ppm: 27.84 (3-CH_2); 31.37 (5-CH_2); 37.51 (7'-CH_2); 46.16 (5'-NCH_3); 46.23 (1-NCH_3); 52.61 (C-4); 52.89 (2-CH_2 and 6-CH_2); 55.64 (4'-CH_2); 55.82 (6'-CH_2); 61.79 (3a'-CH); 155.19 (7a'-C). Mass spectrum, *m/z* (I_{rel}, %): 222 $[M]^+$ (3.7), 464 $[M–H]^+$ (20.6), 152 (9.8), 151 (100), 108 (16.1), 107 (5.9), 77 (5.1), 58 (15.7), 44 (32.2), 43 (15.0), 42 (40.7), 36 (40.4).

1,5'-Dibenzyl-2',3a',4',5',6',7'-hexahydrospiro[piperidine-4,3'-pyrazolo[4,3-*c*]pyridine] (7f). Cream crystalline material, trihydrobromide – white colored; mp of trihydrobromide of **7f** 216–217ºC (decomp.). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.57–1.62 (2H, m, H-5); 1.65–1.71 (1H, m, H-7'); 1.81 (1H, ddd, J_1 = 13.2, J_2 = 11.0, J_3 = 4.2, H-7'); 2.02–2.09 (2H, m, H-2 and H-4'); 2.11–2.23 (2H, m, H-6,6'); 2.41–2.50 (1H, m, H-3); 2.51–2.56 (1H, m, H-3); 2.67–2.76 (3H, m, H-6, H-4',6'); 2.97 (1H, ddd, J_1 = 10.3, J_2 = 6.1, J_3 = 1.8, H-3a'); 3.04–3.09 (1H, m, H-2); 3.50 (2H, s, 1-PhC$\underline{H}_2$N); 3.59 and 3.62 (2H, 2d, *J* = 13.3, 5'-PhC$\underline{H}_2$N); 5.41 (1H, br. s, NH); 7.26–7.36 (10H, m, 2Ph). ^{13}C NMR spectrum, δ, ppm: 27.94 (3-CH_2); 31.46 (5-CH_2); 37.58 (7'-CH_2); 50.41 (C-4); 50.92 (4'-CH_2); 53.38 (6'-CH_2); 53.51 (2-CH_2 and 6-CH_2); 53.85 (3a'-CH); 62.64 (5'-Ph$\underline{C}H_2$N); 63.23 (1-PhCH_2N); 127.28 and 127.32 (4"-CH Ph); 128.39 and 128.45 (3"(5")-CH Ph); 128.99 and 129.28 (2"(6")-CH Ph); 138.16 and 138.28 (C-1" Ph); 156.01 (7a'-C). Mass spectrum, *m/z* (I_{rel}, %): 374 $[M]^+$ (1.0), 283 $[M–Bn]^+$ (5.8), 241 (8.2), 240 (18.0), 227 (43.7), 148 (12.6), 134 (21.6), 109 (21.6), 91 $[Bn]^+$ (100), 65 (16.4), 42 (35.4), 41 (13.2).

N-(3-[4-(Benzoylamino)-1-benzyl-1,2,5,6-tetrahydropyridin-3-yl]-1-benzylpiperidin-4-ylidene)benzamide (8). Pyridine (2 ml) and then, dropwise, benzoyl chloride (1.2 g, 8.5 mmol) were added to a solution of the azine **4f** (1.5 g, 4.0 mmol) in *o*-xylene (10 ml). The mixture was stirred at room temperature for 30 min and then refluxed for 36 h under an argon atmosphere. The reaction mixture was evaporated to dryness and the residue was washed with sodium bicarbonate solution and extracted with methylene chloride (3×30 ml). The extracts were dried over sodium sulfate, evaporated to dryness, and the residue was then chromatographed on silica gel (ethyl acetate–methanol, 25:1) to give a yellowish, crystalline product (1.7 g, 92%); mp 152–153ºC. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.40–1.44 (1H, m, H*a*-5); 1.63–1.71 (1H, m, H*e*-5); 2.20–2.26 (1H, m, H*a*-6'); 2.28–2.34 (1H, m, H*a*-6); 2.38 (1H, dd, J_1 = 12.5, J_2 = 4.5, H*a*-2'); 2.41–2.47 (1H, m, H*e*-6'); 2.56–2.60 (1H, m, H*e*-6); 2.61–2.67 (1H, m, H*a*-5'); 2.79 (1H, dd, J_1= 12.5, J_2 = 2.0, H*e*-2'); 2.83–2.87 (1H, m, H*e*-5'); 3.00 (1H, m, H*a*-2); 3.06 (1H, m, H*e*-2); 3.41 and 3.64 (2H, 2 d, *J* = 16.2, 1'-PhC$\underline{H}_2$N); 3.59 (2H, s, 1-PhC$\underline{H}_2$N); 4.42 (1H, m, H-3'); 7.09 (1H, br. s, NH); 7.25–7.49 (16H, m, Ph); 7.57 (2H, dd, J_o = 7.1, J_m = 1.3, H-*o* PhCO); 7.81 (2H, dd, J_o = 7.1, J_m = 1.3, H-*o* PhCO). ^{13}C NMR spectrum, δ, ppm: 27.15 (5-CH_2); 34.83 (5'-CH_2); 42.92 (3'-CH_2); 49.56 (6-CH_2); 49.90 (2-CH_2); 49.92 (6'-CH_2); 50.41 (2'-CH_2); 62.40 (1'-Ph$\underline{C}H_2$N); 63.08 (1-Ph$\underline{C}H_2$N); 120.86 (C-3); 127.29; 127.34; 128.39; 128.62; 129.15; 129.28; 130.82; 132.34 (C-1 PhCON=); 135.35 (C-1 PhCONH); 137.37 (C-4); 138.17 (C-1 Bn); 138.62 (C-1 Bn); 167.55 (CO PhCONH); 168.42 (C-4'); 171.01 (CO PhCON=). Mass spectrum, *m/z* (I_{rel}, %): 461 $[M–BzNH_2]^+$ (3.0), 342 (13.5), 237 (7.7), 122 (5.2), 105 $[PhCO]^+$ (100), 91 $[Bn]^+$ (94.5), 77 $[Ph]^+$ (51.9), 65 (9.5), 51 (14.1). Found, %: C 78.33; H 6.41; N 9.48. $C_{38}H_{38}N_4O_2$. Calculated, %: C 78.32; H 6.57; N 9.61.

2,8-Dibenzoyl-2,3,4,5,6,7,8,9-octahydro-5H-pyrrolo[3,2-*c*:4,5-*c*']dipyridine (5b). A solution of azine **4b** (21.7 g, 54.0 mmol) in diphenyl oxide (30 ml) was heated for 4–6 h at 210–220ºC under an argon atmosphere. The reaction mixture was cooled, benzene (50 ml) was added with stirring, and petroleum ether (80 ml) was added slowly. The precipitate formed was stirred for 20–30 min, filtered, washed with a mixture of benzene and petroleum ether (1:3, 100 ml), and dried in air to give a light-cream, crystalline material (19.7 g, 95%) with mp 237–238ºC. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.60–2.81 (4H, m, H-4(6)); 3.55–4.09 (4H, m, H-3(7)); 4.27–4.80 (4H, m, H-1(9)); 7.32–7.51 (10H, m, 2Ph); 8.00 (1H, br. s, NH). ^{13}C NMR spectrum, δ, ppm: 23.88 and 22.93 (4-CH_2 and 6-CH_2); 40.25 and 40.68 (1-CH_2 and 9-CH_2); 45.39 and 45.64 (3-CH_2 and 7-CH_2); 110.26 and 110.73 (C-9a,9b); 123.10 and 123.30 (C-4a,5a); 126.86 (2-CH and 6-CH Ph); 128.61 (3-CH and 5-CH Ph); 129.82 (4-CH Ph); 136.12 (C-1 Ph); 171.12 (C=O). Mass spectrum, *m/z* (I_{rel}, %): 385 $[M]^+$ (3.4); 280 $[M–Bz]^+$ (4.0), 264 (12.2), 251 (16.9), 159 (22.8), 147 (16.3), 132 (15.3), 119 (15.2), 105

$[Bz]^+$ (100), 78 (13.8), 77 $[Ph]^+$ (85.1), 51 (25.8). Found, %: C 74.72; H 5.97; N 11.00. $C_{24}H_{23}N_3O_2$. Calculated, %: C 74.78; H 6.01; N 10.90.

2,8-Dibenzyl-1,2,3,4,6,7,8,9-octahydro-5H-pyrrolo[3,2-*c*:4,5-*c*']dipyridine (5f). Compound **5b** (19.7 g, 51.0 mmol) was added portionwise with vigorous stirring to a suspension of lithium aluminum hydride (3.8 g, 100 mmol) in anhydrous THF (300 ml) and the mixture was refluxed for 8 h. The product was cooled and water (4 ml) was added followed by NaOH solution (15%, 5 ml) and further water (4 ml). The reaction product was then filtered and the precipitate on the filter was washed several times with hot THF (3×40 ml). The filtrate obtained was dried over sodium sulfate and evaporated to dryness. The residue was dissolved in toluene (70 ml), evaporated to constant weight, and recrystallized from ethanol to give a white or cream colored material (15.6 g, 86%); mp 177–178ºC. ^{1}H NMR spectrum, δ, ppm: 2.66 (4H, t, J = 5.5, H-4(6)); 2.77 (4H, t, J = 5.5, H-3(7)); 3.37 (4H, s, H-1(9)); 3.71 (4H, s, PhC$\underline{H}_2$); 7.25–7.28 (2H, m, H-4 Ph); 7.31–7.35 (4H, m, H-3(5) Ph); 7.38–7.42 (4H, m, H-2(6) Ph); 7.46 (1H, br. s, NH). ^{13}C NMR spectrum, δ, ppm: 23.46 (4-CH_2 and 6-CH_2); 50.21 (3-CH_2 and 7-CH_2); 50.48 (1-CH_2 and 9-CH_2); 112.53 (C-9a,9b); 123.58 (C-4a,5a); 127.09 (4-CH Ph); 128.36 (3-CH and 5-CH Ph); 129.14 (2-CH and 6-CH Ph); 139.13 (C-1 Ph). Mass spectrum, *m/z* (I_{rel}, %): 357 $[M]^+$ (4.0); 238 $[M–BnN=CH_2]^+$ (38.3), 146 (7.1), 145 (7.1), 120 (13.7), 119 $[M-2BnN=CH_2]^+$ (48.7), 91 $[Bn]^+$ (100), 65 (15.1). Found, %: C 80.56; H 7.43; N 11.74. $C_{24}H_{27}N_3$. Calculated, %: C 80.63; H 7.61; N 11.75.

5H-Pyrrolo[3,2-*c*:4,5-*c*']dipyridine (3,6-Diazacarbazole, 8-Aza-γ-carboline) (10). A. Compound **5b** (0.5 g, 1.30 mmol) was added to a suspension of palladium on carbon (10%, 0.2 g) in diphenyl oxide (10 ml) and the mixture was heated for 6 h at 160–170ºC under an argon atmosphere. The product was cooled and toluene (20 ml) and hydrochloric acid (1 N, 20 ml) were added. The aqueous phase was washed with more toluene (10 ml) and basified to pH 9.0 with aqueous potassium hydroxide solution. The mixture obtained was evaporated to dryness and the residue was extracted with ethanol (3×10 ml). The alcohol solution was evaporated to dryness and the residue was recrystallized from water to give a light-gray, crystalline material (0.048 g, 22%) with mp 312–313ºC (subl.) (mp > 300ºC [24]), mp 344–347ºC [25], mp 328ºC [26]).

B. The conditions and separation process for the target compound were similar to method A but using palladium on carbon (10%, 0.13 g) in diphenyl oxide (7 ml) and compound **5f** (0.24 g, 0.67 mmol) to give a light-gray, crystalline material with mp 314–315ºC (subl.).

C. Compound **5f** (0.8 g, 2.0 mmol) was added to a suspension of palladium on carbon (10%, 0.4 g) in mesitylene (15 ml) and refluxed for 90 min. The product was cooled and toluene (15 ml) and hydrochloric acid (2 N, 15 ml) were added. The aqueous phase was separated, washed with toluene (10 ml) and basified to pH 9.0 with an aqueous solution of potassium hydroxide. The precipitated material was filtered off and recrystallized from water to give a light-gray, crystalline material (0.25 g, 74%); mp 315–316ºC (subl.). ^{1}H NMR spectrum (DMSO-d_6), δ, ppm (J, Hz): 7.56 (2H, d, J = 5.7, H-4,6); 8.51 (2H, d, J = 5.7, H-3,7); 9.45 (2H, s, H-1,9); 12.05 (1H, br. s, NH). ^{13}C NMR spectrum, δ, ppm: 107.40 (4-CH and 6-CH); 117.83 (C-9a,9b); 143.10 (3-CH and 7-CH); 144.00 (C-4a,5a); 145.39 (1-CH and 9-CH). Mass spectrum, *m/z* (I_{rel}, %): 169 $[M]^+$ (100); 142 $[M–HCN]^+$ (10.0), 141 (9.5), 115 $[M–2HCN]^+$ (8.5), 114 (12.6), 88 (12.5), 87 (12.2), 75 (16.8), 74 (14.8), 63 (19.3), 62 (18.1), 52 (29.1), 51 (11.3), 50 (14.2), 40 (23.6), 39 (12.4), 38 (12.5). Found, %: C 68.07; H 4.30; N 23.75. $C_{10}H_7N_3 \cdot 0.4H_2O$. Calculated, %: C 68.09; H 4.46; N 23.82.

REFERENCES

1. O. Piloty, *Chem. Ber*., **43**, 489 (1910).
2. G. M. Robinson and R. Robinson, *J. Chem. Soc.*, **113**, 639 (1918).
3. K. V. Vatsuro and L. G. Mishchenko, *Named Reactions in Organic Chemistry* [in Russian], Khimiya, Moscow (1976), p. 319.
4. W. H. Perkin and S. G. P. Plant, *J. Chem. Soc.*, **127**, 1138 (1925).
5. A. N. Kost and I. I. Grandberg, *Zh. Obshch. Khim.*, **26**, 565 (1956).
6. W. H. Perkin and S. G. P. Plant, *J. Chem. Soc.*, **125**, 1503 (1924).

7. B. Robinson, *Chem. Rev.*, **63**, 373 (1963).
8. H. Posvic, R. Dombro, H. Ito, and T. Telinski, *J. Org. Chem.*, **39**, 2575 (1974).
9. J. E. Baldwin and J. C. Bottaro, *J. Chem. Soc., Chem. Commun.*, 624 (1982).
10. M. R. Rivero and S. E. Buchwald, *Org. Lett.*, **9**, 973 (2007).
11. B. C. Milgram, K. Eskildsen, S. M. Richter, W. R. Scheidt, and K. A. Scheidt, *J. Org. Chem.*, **72**, 3941 (2007).
12. H. Tanaka, M. Moriwaki, and T. Takahashi, *Org. Lett.*, **5**, 3807 (2003).
13. Y. Tamaru, T. Harada, and Z. Yoshida, *J. Org. Chem.*, **43**, 3370 (1978).
14. G. Laber, *Liebigs Ann. Chem.*, **588**, 79 (1954).
15. A. N. Kost and I. I. Grandberg, *Zh. Obshch. Khim.*, **25**, 2064 (1955).
16. V. V. Bagutskii and O. G. Kulinkovich, *Khim. Geterotsikl. Soedin.*, 617 (2000). [*Chem. Heterocycl. Comp.*, **36**, 537 (2000)].
17. Enraf-Nonius (1994). *CAD4 EXPRESS*. Enraf-Nonius, Delft, The Netherlands.
18. G. M. Sheldrick, *Acta Crystallogr.*, **A64**, 112 (2008).
19. L. J. Farrugia, *J. Appl. Crystallogr.*, **30**, 565 (1997).
20. F. Uhlig, *Angew. Chem.*, **66**, 435 (1954).
21. S. M. McElvain and R. E. McMahon, *J. Am. Chem. Soc.*, **71**, 901 (1949).
22. J. L. Vennerstrom, Y. Dong, J. Chollet, and H. Matile, US Pat. 6486199; www.espacenet.com .
23. A. S. Bailey, C. M. Birch, D. Illingworth, and J. C. Willmott, *J. Chem. Soc., Perkin Trans.* 1, 1471 (1978).
24. Ł. Kaczmarek, A. Bęcalski, and P. Nantka-Namirski, *Polish J. Chem.*, **54**, 1585 (1980).
25. J. Kalinowski, A. Rykowski, and P. Nantka-Namirski, *Polish J. Chem.*, **58**, 125 (1984).
26. E. Koenigs and P.-L. Nantka, *Ber.*, **74**, 215 (1941).